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SWITCH-China: A Systems Approach to Decarbonizing China's Power System

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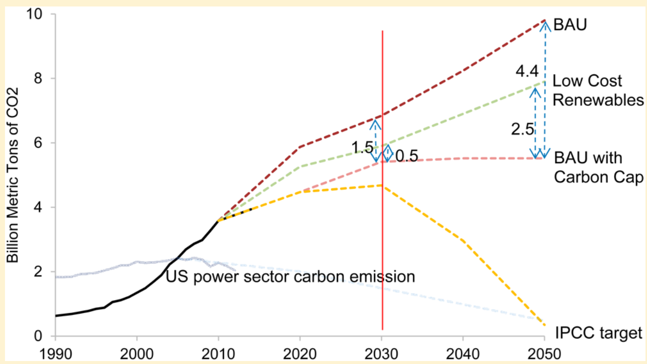
Supporting Information

ABSTRACT: We present an integrated model, SWITCH-China, of the Chinese power sector with which to analyze the economic and technological implications of a medium to long-term decarbonization scenario while accounting for very-short-term renewable variability. On the basis of the model and assumptions used, we find that the announced 2030 carbon peak can be achieved with a carbon price of ∼\$40/t_{CO_2}. Current trends in renewable energy price reductions alone are insufficient to replace coal; however, an 80% carbon emission reduction by 2050 is achievable in the Intergovernmental Panel on Climate Change Target Scenario with an optimal electricity mix in 2050 including nuclear (14%), wind (23%), solar (27%), hydro (6%), gas (1%), coal (3%), and carbon capture and sequestration coal energy (26%). The co-benefits of carbon-price strategy would offset 22% to 42% of the increased electricity costs if the true cost of coal and the social cost of carbon are incorporated. In such a scenario, aggressive attention to research and both technological and financial innovation mechanisms are crucial to enabling the transition at a reasonable cost, along with strong carbon policies.



■ INTRODUCTION

Today, China's power sector accounts for 50% of the country's total greenhouse-gas emissions and 12.5% of the global energy-related carbon emissions.[1] The transition from the current fossil-fuel-dominated electricity supply system to a sustainable, resource-wise system will shape how the country (and, to a larger extent, the world) address local pollution and global climate change. Although coal is the dominant energy source today, ongoing rapid technological changes coupled with strategic national investments in transmission capacity and new nuclear, solar, and wind generation demonstrate that China has the capacity and willingness to perform a thorough energy transition.[2,3] The progression to a low-carbon development, in fact, is the official goal of the Chinese government. In the 2014 United States−China joint announcement on climate change and China's intended national determined contribution (INDC), China announced its determination to peak its carbon emissions around 2030 and reach 20% of nonfossil sources in its primary energy mix by the same year.[4,5] Installed wind capacity has sustained a remarkable 80% annual growth rate since 2005, making China a global leader with over 95.81 gigawatts (95.81 GW; and 7% of national capacity, or C_N, capacity) of installed capacity in 2014, while the United States rank second with 65.88 GW (6% of C_N), and Germany is third with 39 GW (21% of C_N).[6,7] China's solar-power installed capacity has also been growing at an unprecedented pace. Its grid-connected solar photovoltaic (PV) capacity has reached 28.05 gigawatts (GW) by the end of 2014 (2% of C_N), a 30-fold increase in four years from 0.90 GW in 2010.[8−10] In addition, half of all of the new nuclear power plants planned by 2030 worldwide are to be built in China. However, the multitude of wind- and solar-power curtailment in China highlights the necessity to perform a thorough planning to optimize the installation of such systems in parallel with the transmission network and storage technologies.

The efficient use of this new generating capacity and the integration of even larger quantities of clean energy require a platform in which investment and operational decisions can be

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optimized to meet reliability and cost management objectives on a previously unstudied scale, particularly for rapidly growing cities. Carbon capture and sequestration (CCS), shale-gas development, and new hydropower infrastructure all add additional complexity to this system. Lacking from the discussion of these resources is an open-access platform to explore the implications of different investment options for energy generation and transmission in China, as well as a means to examine the implications of different operating decisions and network topologies. Such a tool would enhance the opportunity for shared learning and dialogue around the engagement in a cost-effective decarbonization of the electricity system. The SWITCH-China model presented in this paper fills this need.

■ MATERIALS AND METHODS

A range of models exist that provide important perspectives on China's long-term energy supply and demand challenges.[11−15] Macroscale models provide insights into the resource constraints that national and regional energy systems face.[16,17] For China, these models mainly focus on the management of coal as a main future energy source because of its current predominance in the country's electricity mix.[16,18,19] Existing studies that use an optimization model to identify the best pathways for long-term electricity mix transition[20−24] have low geographical and temporal resolutions that are often limited to national scale and annual demand, therefore not accounting for the crucial role of electricity transmission as well as the short-time-scale variability of renewable energies. For the exploration of the realistic management of energy generation and transmission assets, a new generation of big-data models is needed. To address this need, we have developed a high-resolution integrated model that accurately reflects the performance of each element of the electricity system.[25]

Explorations of the opportunity for China to transition to a low-carbon power sector must be performed through an accurate representation of the performance of variable solar and wind resources so that the overall system's reliability and costs can be evaluated. Only within this framework can the impacts of physical transmission bottlenecks, supply constraints, and realistic policy choices be studied. Because the multidimensional scope of energy models are limited by computing time, SWITCH-China favors an accurate representation of the grid operation, through high spatial and temporal resolution, over a larger scope that would include not only the electricity mix but also transportation and heating.

The SWITCH model is a linear program whose objective function is to minimize the cost of producing and delivering electricity through the construction and retirement of various power generation, storage, and transmission options between present day and future target dates (over the 2050 horizon) according to projected demand. SWITCH optimizes both the long-term investment and the short-term operation of the grid. It uses a combination of existing and new grid assets. Optimization is subject to reliability, operational, and resource-availability constraints as well as both existing and possible future climate policies.[26−29] In SWITCH-China, we parametrize the entire power system as an optimization problem, permitting studies of the most cost-effective long-term investment and operational decisions across China.

A set of models exist to demonstrate that deep decarbonization (generally taken as 80% or more reductions in total CO_2 emissions) in the power sector by 2050 is physically possible for regions of the United States.[30−35] The overwhelming dominance of coal in China today implies that models simply based on aggregate resources of fossil fuels, hydropower, and variable renewable resources are not sufficient to examine how a transition to a low-carbon future can be managed from operational and financial standpoints. We use the SWITCH-China model to combine high spatial and temporal fidelity with detailed information on both renewable energy resources as well as on the cost and performance of specific energy technologies. This combination is needed to explore the cost and reliability impacts of specific policy choices to help China meet its future energy and environmental targets. SWITCH-China builds on detailed resource potential assessment of wind and solar availability at provincial level[7,36] and uses time-synchronized historical hourly load and generation profiles at the provincial scale. Cost, construction time, and technological performance projections are exogenous (Supporting Information page S30), and so is future electricity demand calculated at the State Grid Energy Research Institute located in Beijing (Supporting Information page S24). Assumptions for future generation technologies, including CCS and storage technologies, are provided in Supporting Information page S29.

We consider four major scenarios: a Business-as-Usual ("BAU") scenario for which no carbon constraints are applied, a Business-as-Usual with Carbon Cap scenario, which differs from the BAU scenario only by the inclusion of China's official 2030 carbon constraints, a Low-Cost Renewables scenario, and an IPCC Target scenario (see Table 1).

Table 1. Model Scenario Description

scenarios	carbon constraints
Business-As-Usual ("BAU")	2010 base, no carbon constraints
Business-As-Usual with Carbon Cap ("BAU with Carbon Cap")	2020 carbon intensity target and 2030 peak emission commitment
Low-Cost Renewables ("Low Cost Renewables")	2010 base, aggressive wind and solar learning curve, no carbon constraints
IPCC Target ("IPCC Target")	2020 carbon intensity target, 2030 peak emission, and 2050 80% carbon reduction on 1990 level

The assumptions in the Business-as-Usual Scenario and Business-as-Usual with Carbon Cap Scenario ("BAU with Carbon Cap" hereafter) are consistent with the current projections for future technology costs. Future availability and costs of fossil fuel, nuclear, hydropower, and renewable energy assets are exogenous data. "BAU with Carbon Cap" reflects China's existing carbon policies: its 2020 carbon intensity target and 2030 peak-carbon commitment.

In the Low-Cost Renewables scenario ("Low-Cost Renewables" hereafter), we model high levels of cost declines in wind and solar technologies. This scenario provides a particular insight into the impacts of recent significant investments in "cleantech", with only a few examples of successful integrated national climate strategies. This scenario is an aggressive scale-up of a number of technology-oriented efforts, similar to the U.S. *SunShot*[29] program and the U.S. national roadmap for wind power. This scenario is consistent with the country-supported growth of solar and wind manufacturing and deployment in China.[37] Specifically, we assume that the overnight cost of wind will decrease to half of its 2010 costs by 2020, and then it will remain stable at the 2020 level until 2050. Solar cost will decrease until it reaches the value provided by the Solar Shot initiative in 2020[38] and then maintain its 2020 level until 2050. We use a cost for storage

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consistent with the projection by U.S. ARPA-E program.[39] No carbon constraints are applied in this scenario.

In the IPCC Target scenario ("IPCC Target"), we restrict the "BAU with Carbon Cap" further by adding an overall carbon emission target of 80% below the 1990 level baseline in 2050, as proposed in the 2 °C scenario recommended by the Intergovernmental Panel on Climate Change (IPCC).[40]

China currently has existing policy targets in place to reach 15% of primary energy from nonfossil sources by 2020 and newly updated to 20% by 2030 (100 GW for solar and 200 GW for wind energy as proposed in "Energy Development Strategy Action Plan 2014–2020").[2,4,5,41,42] In addition, China has targets in place of 40 to 45% reductions in carbon intensity below the 2005 level by 2020 and has announced an extension of efforts to achieve 60 to 65% reductions by 2030 and peak carbon emissions around 2030.[5] Today, China is well on track to achieve its short-term energy targets, with more wind and solar capacity installed each year than what would be needed to achieve those targets (Table SI-2). However, long-term carbon mitigation and technology pathways are more uncertain.

RESULTS

Starting from the base-year 2010 electricity supply mix, the existing transmission network, and base-year electricity prices, SWITCH-China calculates that a carbon price of \$30/tCO_2 is needed to achieve the 45% carbon intensity target in 2020. A carbon price of \$40/tCO_2 is needed to peak CO_2 emissions in 2030. We find that a carbon price would boost the installation of wind and solar as well as the transition from planned coal facilities to nuclear and natural gas. A carbon price is not as hypothetical as one could think. China has already launched several cap-and-trade pilot programs in Beijing, Shanghai, Tianjin, Guangdong, Shenzhen, Wuhan, and Chongqing,[43,44] with a price range of RMB20–130 (\$3-\$20). Extending this program to a nationwide system is, in fact, the stated national cap-and-trade program that will be set up as early as 2017. A total of \$30/tCO_2 by 2020 and \$40/tCO_2 by 2030 is not a great transition from existing carbon markets.

We find that China's 2020 energy-intensity target and continuous commitment to peak its carbon emissions by 2030 heavily impact the final-power-sector emissions and technology choices. A 40–45% carbon intensity reduction below the 2005 level translates into maintaining the total annual carbon emission between 4.5 and 4.9 Bt CO_2, whereas the "BAU" scenario shows that carbon emissions would be 8.1 Bt CO_2 in 2020.[45] The 2030 commitment as modeled in the "BAU with Carbon Cap" scenario is a real diversion from the "BAU" scenario, where China will have to curb its power sector emissions by 1.5 BtCO_2 by 2030 compared to the "BAU" scenario and by 0.5 BtCO_2 by 2030, even with low-cost renewables (see Figure 1).

By comparing the "BAU" and "Low-Cost Renewables" scenarios, we observe that a renewable technology-oriented policy driven by a large manufacturing base and low prices, as seen in recent years, is important but not sufficient to significantly reduce the rate of deploying new coal-fired power plants and, thus, the growth in carbon emissions. The "Low-Cost Renewables" scenario shows that an aggressive learning curve for renewables would replace about 300 GW of coal compared to the "BAU" scenario by 2050. In addition, this scenario deploys 40 GW more gas capacity between today and 2050 than the "BAU" scenario thanks to this source's flexibility in ramping up and down to integrate variable resources until 2050. Despite this, coal and coal with CCS would still dominate the energy mix by 2050,

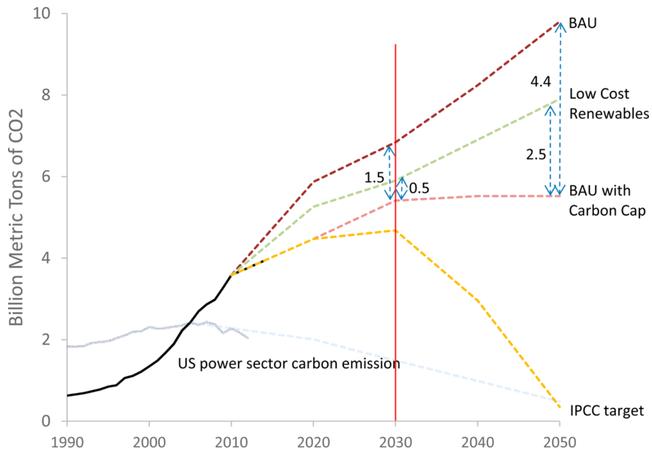

Figure 1. Carbon-emission trajectory for the Chinese power sector under the four scenarios.

representing 70% of total electricity generation under the "BAU" scenario and still providing 62% of total electricity in the "Low-Cost Renewables" scenario in 2050.

Although an 80% carbon emission reduction by 2050 cannot be reached solely by low-cost renewables, it is however achievable by a combination of solar, wind, storage, nuclear, and CCS at high cost if no major technological innovation happens until then. In the medium- and long-term, nuclear energy becomes competitive in this scenario because its high capacity factor provides a stable baseload with little carbon emissions, and it is installed to its maximum reasonable capacity by 2050, about 300 GW. A total of 80% of the 1000 GW coal capacity needs to be coupled with CCS systems. The remaining demand will be met with wind and solar capacities, which together will supply 60% of the total demand in 2050. Electricity costs change from \$64.3/MWh in the "BAU" scenario to \$87.8/MWh in the "IPCC Target" scenario in 2050, a 37% increase driven by the large-scale installation of wind, solar, CCS, and storage (Figure 2).

High penetration of wind and solar systems by 2050 challenges the operation of the grid. With such a large expansion in variable energy resources, a large-scale deployment of storage assets to smooth the output, and an increase in baseload nuclear energy, the operation of the country's power system is no easy task. The system dispatch (Figure 3) shows seasonal pattern of renewable electricity generation. Wind has better availability in winter and spring, and solar and hydropower are more productive during summer and fall. The ramp-up and-down of solar energy during the daytime creates significant needs for short-term storage, even though solar energy matches peak demand fairly well. The role of natural gas is limited despite its flexibility because of its comparatively high price and carbon-emission rate. In the model simulation, flexible load is met by a combination of wind, solar, natural gas, and hydro power and storage.

As of 2013, the global installed capacity of grid energy storage is 130 GW, and China accounts for 17% of this amount, with about 22 GW.[46] Our results show that by 2050, China will need 600 GW of storage to integrate variable wind and solar resources in the "IPCC Target" scenario, which represents twice the amount of estimated additional grid-connected electricity storage capacity (310 GW) needed in the United States, Europe, China, and India, an estimate based on the results of the IEA Energy Technology Perspectives 2014 (ETP 2014) 2 °C scenario (2DS) vision for energy storage.[47] Given China's

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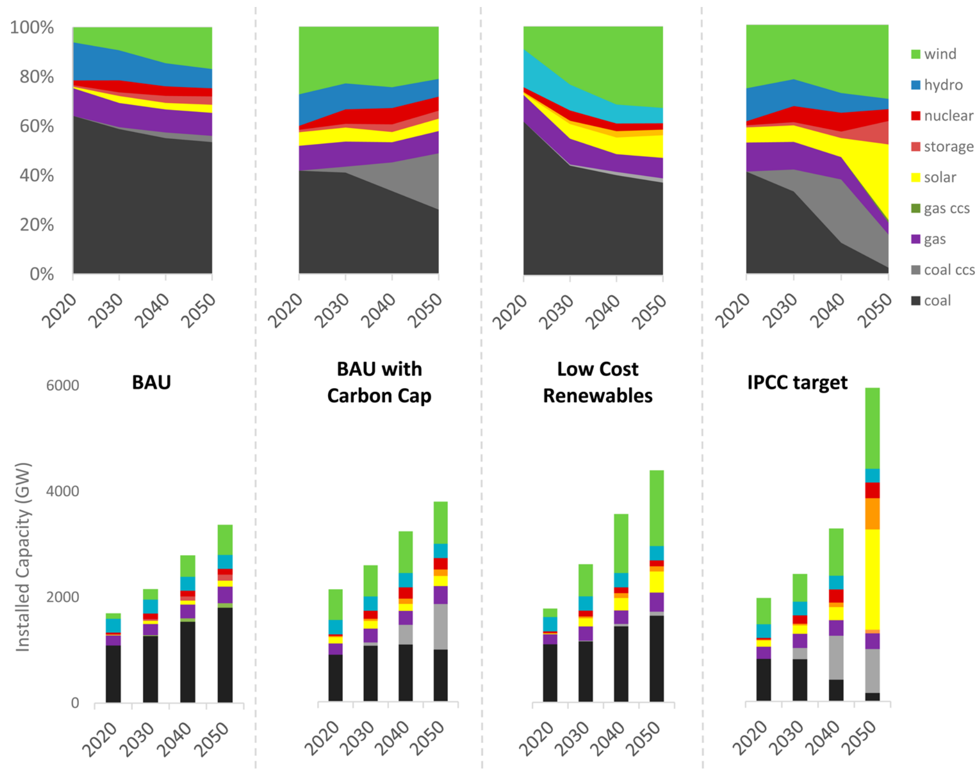

Figure 2. Installed power-generation capacity mix for the four scenarios.

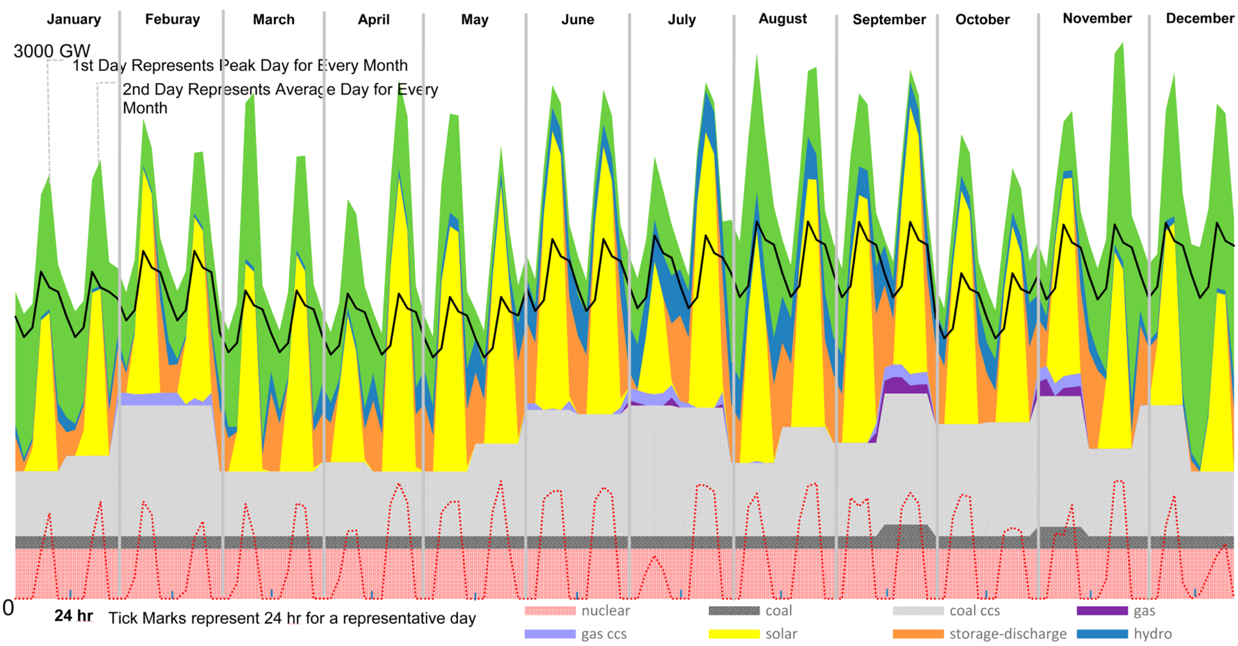

Figure 3. Year 2050 dispatch schedule for "IPCC Target" scenario. Note: an 80% carbon reduction is achievable in China's power system by a combination of wind, solar, storage, CCS, and nuclear power. This system will require a vast storage capacity to provide operational flexibility. Storage charges are 8% of the generation power on average and 26% (maximum) on a storage-incentive day when solar generation is peaking. Storage discharge provides (on average) 9% of system load and 30% (maximum) on a storage-incentive day during night-time when 1000 GW scale solar is offline.

plans to have 70 GW of pumped hydro storage online by 2020, and on the path to explore its 200 GW pumped hydroenergy potential, the remaining storage capacity needed will have to come from other sources. This requires the development of novel storage technologies that have not been implemented on a large scale yet.

Decarbonizing China's power sector would also require new electricity-transmission lines to connect electricity-generation regions and demand centers. The optimal electricity mix constrained by the 2020 national target and the 2050 "IPCC Target" shows that coal will largely be phased out by 2050 (Figure 4). Coal plants with CCS are built in provinces where coal prices are comparatively cheap (notably in Xinjiang, Inner

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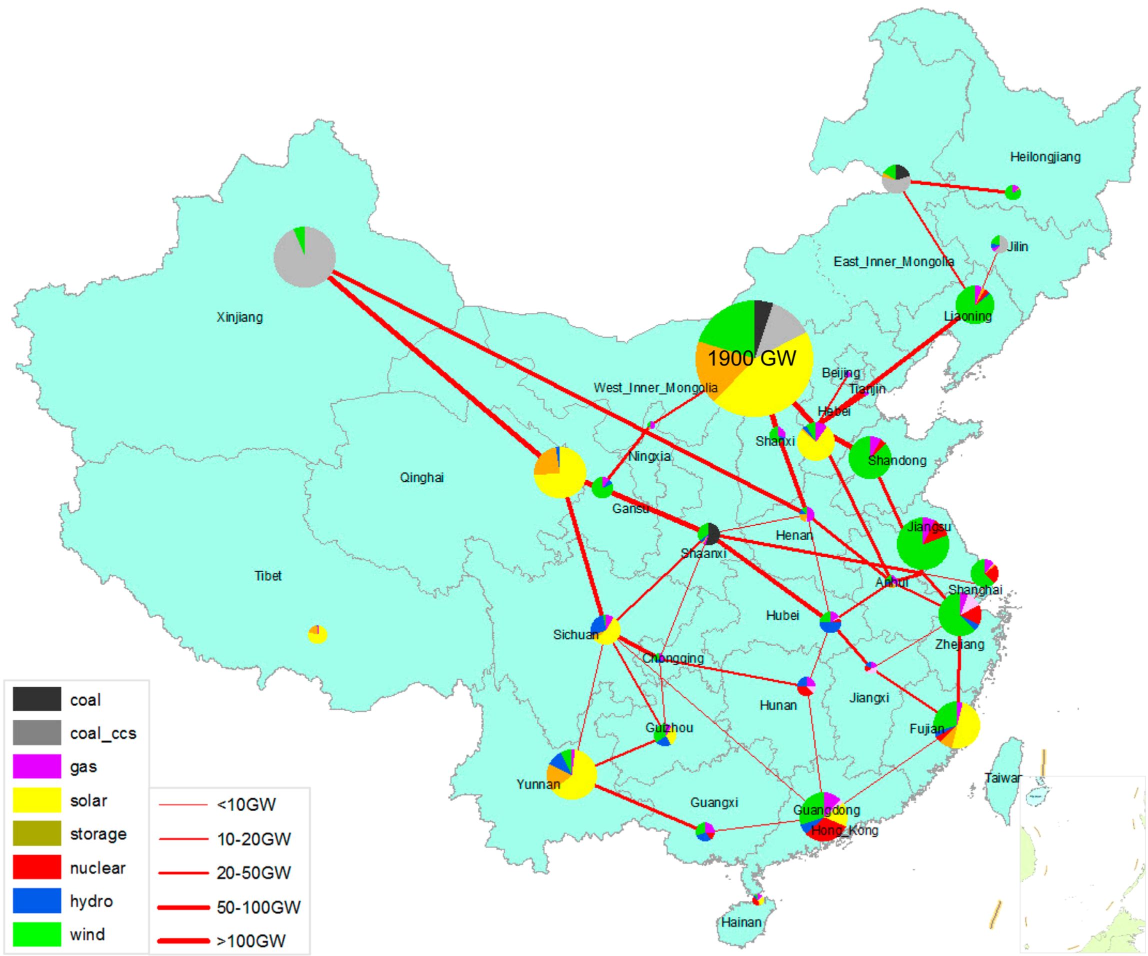

Figure 4. Infrastructure, generation, and transmission capacity needed to achieve an 80% carbon reduction in 2050. All represented lines are new transmission expansion. Inner Mongolia emerges as a major center of clean-energy generation thanks to the combination of its location (a few hundred kilometers from major demand centers) and high-quality renewable energies.

Mongolia, Shaanxi, and Jilin). Nuclear capacity would significantly expand on the country's eastern coast. Several provinces present high potentials for solar and wind power. Large transmission capacity is built to send power from Xinjiang, Qinghai, Inner Mongolia, and Shaanxi to Beijing, Tianjin, Shanghai, Zhejiang, Guangdong, and other coastal demand centers. Transmission capacity makes coal in Xinjiang available at a competitive cost, although the province shows high-quality wind and solar. This unintended consequences of transmission expansion need to be addressed in the planning process. Tibet has good potential for wind and solar; however, transmission infrastructure will not be built in this province because of its remote location unless related transmission costs decrease significantly over the study period.

National policy actions consistent with the "IPCC Target" scenario would have a high positive impact on fuel-cost saving, air-pollution reduction, and other co-benefits. Increased energy costs resulting from this strategy would be partially offset by the decrease in costs from lower environmental pollution as well as public health and climate benefits. To quantitatively capture the benefits in concept, we use the results from emerging literature on the "external cost of coal", which include the life-cycle environmental cost of the coal value chain.[48−50] The external cost of coal in China is reported to range between 204.76 RMB/t (~$30 $/t) and 260 RMB/t (~$40 $/t);[49−51] the resulting benefits from reduced coal represent between 500 and 950 billion USD. The extra cost of the "IPCC Target" scenario is 2269 billion USD annually in 2050 compared to the "BAU" scenario. The benefits of a decarbonized power sector would therefore offset 22% to 42% of the increased power cost in 2050 (Table S8).

DISCUSSION

By optimizing capacity expansion and hourly generation dispatch simultaneously, SWITCH-China is uniquely suited to explore both the value of and synergies among various power-system technology options, providing policymakers and industry leaders with important information about the optimal development of the electricity grid. SWITCH-China helps identify the least-expensive response to achieving national energy and climate targets: we demonstrate that a carbon price of \$30/tCO_2 by 2020 is needed to meet the 2020 carbon intensity target and of ~\$40/tCO_2 by 2030 for the 2030 carbon peak commitment.

To reach an 80% reduction in CO_2 emissions by 2050 in line with the IPCC's findings, the resulting optimal electricity mix in 2050 would include nuclear (14%), wind (23%), solar (27%), hydro (6%), gas (1%), coal (3%), and CCS coal (26%) energy. This will result in a 37% increase in total power cost over the "BAU" scenario. In such a scenario, aggressive attention to research and both technological and financial innovation

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mechanisms are crucial to enabling the transition at a reasonable cost along with strong carbon policies.

China's power sector is evolving, and there are many uncertainties that can impact the pathway of decarbonization. We discussed in the Supporting Information in detail the key sensitivities to the cost of carbon, the limit of nuclear energy, and the cost of CCS (Supporting Information page SI−S38). In addition, the currently cited demand projection is driven by GDP growth and energy-efficient technologies, which both include potential uncertainties.[52] Fuel-price fluctuation and new fuel availabilities may also change optimal technology choices and impact the competitive advantage of the various technologies over time. Current cost assumptions embed uncertainties that will appear in the learning curve of new technologies and do not include external costs and systems-integration costs. Other policy developments not directly related to economics, such as nuclear safety and security, public perception, and acceptance of nuclear and hydro projects, may add uncertainty to the applications of available technologies. We plan to include a more robust uncertainty analysis module in the next phase of model development. Future developments of SWITCH-China will also account for demand-side impact by the electrification of transportation and heating, as well as demand response and resource depletion. Co-optimization under carbon, water, and land-use constraints would also be a key theme for future studies. Energy-extraction limitations resulting from a high concentration of wind turbines in the same spot are not currently modeled but might be integrated in a future version of SWITCH-China using a subprovincial spatial resolution.

China's power sector is in the midst of fast development, and today's investment decisions will have a large impact on the country's ability to achieve its environmental and carbon mitigation targets. SWITCH-China is the "facilitator" that helps understand how technologies, policies, and investment decisions can be coupled and enables strategic thinking on the future of China's transition to a low-carbon power system. Concerted action is needed to develop such a system, including introducing a meaningful carbon price, coordinating the investment decisions, and building the necessary infrastructure for moving energy around.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.6b01345.

Additional details on the SWITCH model and data, China's carbon target sand power sector emissions, model scenario descriptions, the benefits of low-carbon power transition, and key sensitivity analysis. Tables showing important sets and indices, investment and dispatch decision variables, objective functions, transmission project costs in regional grids, technology-specific targets in China's power sector, new generator parameters, connection cost types in SWITCH-China, China's national carbon targets in power sectors, wind-cost assumptions, solar-cost assumptions, benefits of China's low-carbon power transition, and carbon price sensitivity assumptions. Figures showing load areas and regional grids in SWITCH-China, typical daily load profiles by hour and yearly load profiles by month, total projected load in 2030 for each load area, China's development of non-fossil-fuel capacity and targets, average coal prices in China in 2010, generator and storage overnight capital costs in each investment period, and the impact of carbon price, nuclear limits, and CCS costs to the capacity mix in 2050. (PDF)

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Notes

The authors declare no competing financial interest.

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