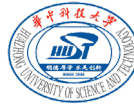


October 2021



HARVARD-CHINA PROJECT
on Energy, Economy and Environment



Rethinking Grid Integration of a Massive Renewable Power Expansion to Achieve Carbon Neutrality in China and Beyond

A Research Brief for Non-Specialists
on a Recent Study in *Joule*



HUAZHONG UNIVERSITY OF SCIENCE AND TECHNOLOGY

State Key Laboratory of Advanced Electromagnetic Engineering and Technology
School of Electrical and Electronic Engineering, Wuhan, China

HARVARD UNIVERSITY

Harvard-China Project on Energy, Economy and Environment
Harvard John A. Paulson School of Engineering and Applied Sciences, Cambridge, MA, USA

TSINGHUA UNIVERSITY

Department of Electrical Engineering, Beijing, China





Acknowledgements

This Research Brief is based on the findings of the following study:

Xinyu Chen, Yaxing Liu, Qin Wang, Jiajun Lv, Jinyu Wen, Xia Chen, Chongqing Kang, Shijie Cheng, and Michael B. McElroy, 2021, “Pathway towards Carbon-Neutral Electrical Systems in China by Mid-Century with Negative CO₂ Abatement Costs Informed by High Resolution Modeling,” *Joule*, 5, 10 (20 October), 2715-2741. Available at <https://doi.org/10.1016/j.joule.2021.10.006>.

The study was supported by the Harvard Global Institute, Energy Foundation China, HUST-State Grid Future of Grid Institute, and National Science Foundation of China.

This Research Brief was sponsored by the Energy Foundation China.

For more information about the Harvard-China Project on Energy, Economy and Environment and its research collaborations with colleagues at Huazhong University of Science and Technology, Tsinghua University, and other universities in China, visit www.chinaproject.harvard.edu.



Key Takeaways

- There are many uncertainties about pathways to mid-century carbon neutrality in China and other major emitting nations, but one fundamental aspect is certain: it will require massive expansions of wind and solar power to displace thermal power generation.
- Sharply expanded *generation* of wind and solar power in China is feasible in geophysical, technical, and economic terms. Posing a greater challenge will be its *grid integration* because of the inherent variability of renewable power compared to thermal power.
- Planning cost-effective grid integration of renewable power requires an analytical scope extending beyond the power system alone, to key elements of the rest of the energy system affecting the timing and flexibility of future electricity demand. These include electrified transportation and “power-to-gas” production of green hydrogen.
- A conventional grid integration strategy including only expanded renewables and power storage optimized on a primarily provincial basis to achieve an 80% decarbonized power sector by 2050 would cost US\$27/ton of abated CO₂ compared to a “business-as-usual” (BAU) pathway without carbon constraints.
- A comprehensive strategy including expanded ultra-high-voltage transmission, national grid interconnection, green hydrogen production, and slow-charging electric vehicle fleets could achieve the same 80% reduction by 2050 at a cost of US\$ -25/ton of CO₂ (i.e., a net benefit) compared to BAU. Contributing to the cost savings are:
 - the increasing feasibility of offshore wind, which is valuable not only because of the size of its potential but also its proximity to China’s largest electricity demand centers on the coast; offshore wind will help shift China’s national transmission structure from the conventional “West-to-East” paradigm of the present to a “Periphery-to-the-Center” one in the decarbonized future;
 - optimized transmission for power balancing on a national rather than provincial basis, which reduces investments in power storage;
 - optimized additions of comparatively flexible power loads of green hydrogen production and slow-charged electric vehicles, which likewise ease power balancing.
- Because of the net benefits under the comprehensive strategy, the 20% of CO₂ emissions from remaining thermal power generation could be mitigated using even costly carbon capture and storage and still achieve a carbon-neutral power sector in 2050 at no net cost compared to BAU.
- The growing feasibility of offshore wind and storage technologies may similarly combine with strategic transmission expansion and new forms of electricity demand to reduce the costs of achieving carbon neutrality in other major emitting nations.



The Central Role of Wind and Solar Power in Achieving Carbon Neutrality

The pathway to mid-century carbon neutrality in any major economy is complex and uncertain, in part because so much can change, in ways we can only roughly project over the decades until 2050.

Some important features of a decarbonized energy economy, however, are widely agreed upon. One of the most important is that renewable electricity is certain to take on a paramount role in our future power systems. Electricity is irreplaceable for modern life and decarbonizing fossil fuel-fired (or “thermal”) power using carbon capture and storage is certain to be costlier than renewables in most circumstances.

A reason this cost-effectiveness projection is widely agreed upon results from perhaps the biggest accomplishment of global clean energy innovation to date: technological and production advances in both solar and onshore wind power generation that are steadily driving their costs below those of even coal-fired generation, the cheapest traditional power source. This looks increasingly likely even for offshore wind over a somewhat

longer term, driven by investments and advances in Europe over the last decade and China more recently. The expanded wind and solar power sources will complement slower-growing capacities of other non-carbon power generation including hydro, which is often cost-competitive but faces resource and other expansion constraints, and nuclear, which is generally not cost-competitive.

The study summarized in this Research Brief (Chen et al. 2021¹) assesses the strategies required to accommodate a massive expansion of renewable power in China to cost-effectively meet its goal of carbon neutrality before 2060. To achieve economy-wide carbon neutrality by that year, including hard-to-abate sectors such as heavy industries and heavy-duty transportation, China’s power system will likely have to be carbon neutral by 2050, the target year for this analysis. The study’s lessons are potentially applicable to similar energy transitions that will be required in other major emitting nations to meet their own carbon neutrality targets in mid-century.

“RENEWABLE
ELECTRICITY
IS CERTAIN TO TAKE
ON A PARAMOUNT
ROLE IN OUR FUTURE
POWER SYSTEMS”

¹Xinyu Chen, Yaxing Liu, Qin Wang, Jiajun Lv, Jinyu Wen, Xia Chen, Chongqing Kang, Shijie Cheng, and Michael B. McElroy, 2021, “Pathway towards Carbon-Neutral Electrical Systems in China by Mid-Century with Negative CO₂ Abatement Costs Informed by High Resolution Modeling,” *Joule*, 5, 10 (20 October), 2715–2741. Available at <https://doi.org/10.1016/j.joule.2021.10.006>.

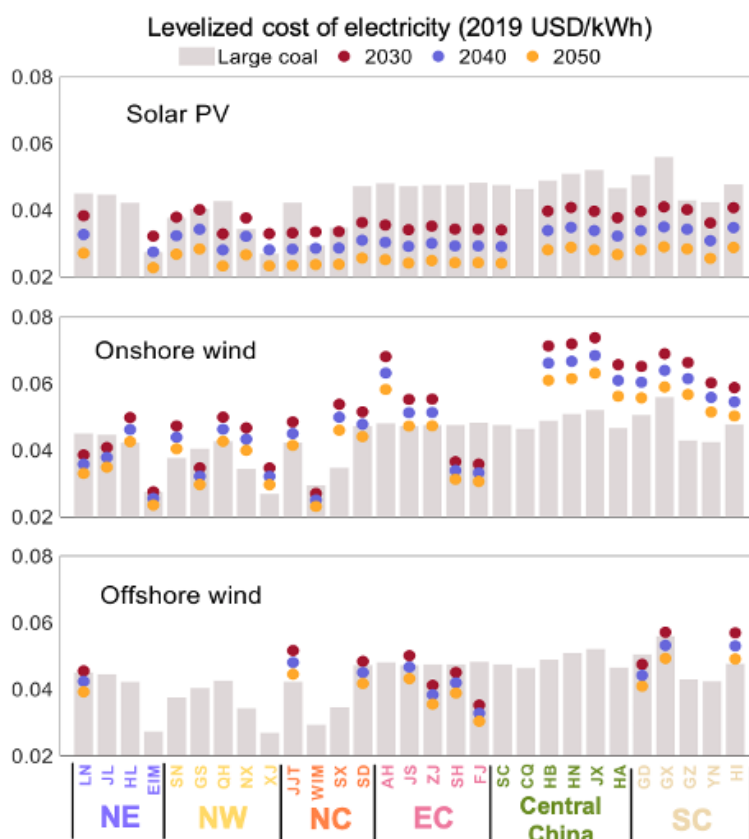
The Cost-Competitiveness of Wind and Solar Power Generation



The analysis begins by evaluating the cost-competitiveness of solar, onshore wind, and offshore wind power generation leading up to and including 2050, without yet considering its grid integration.

Resource potentials and projected generation productivity (“capacity factors”) of solar photovoltaic (PV) and both onshore and offshore wind power generation are quantified based on hourly meteorological data from NASA; availability of land accounting for altitude, slope, and existing land uses; and ocean availability accounting for sea depths, harbors, shipping routes, and protected zones. Combining these factors with current and projected investment and operational costs yields benchmark Levelized Costs of Electricity (LCOEs) for the three subject renewable source types by province, for 2030, 2040, and 2050. These are compared to the LCOEs of large coal-fired units in **Figure 1**. Note that variations in the LCOEs of coal-fired generation result mainly from avoided costs of coal transportation to power plants within major coal-producing provinces.

This initial evaluation reveals that solar PV power generation will be cost-competitive with coal in nearly all provinces by 2030 and its advantages will only grow with time. Onshore wind will be cost-competitive mainly across northern provinces, but not in southern and central regions because of comparatively poor wind conditions. The economic evaluation of offshore wind takes account not only of wind quality but also the distance to shore and sea depth given the need for seafloor transmission. It indicates that it too will be increasingly cost-competitive with coal power in most coastal provinces, if on a somewhat later timeframe.



■ **Figure 1.** Levelized Costs of Electricity for Renewable vs. Coal-Fired Generation in 2030–2050 by Province and Region, in 2019 US\$/kWh

Left image: Fuxian Lake by Luo Lei / Unsplash. Above image: Solar power plant, Shanghai skyline by 安琦王 / Adobe

Challenge of Grid Integration and Value of a High-Resolution Energy Model



Power production facility in China | By 孤飞的鹤 / Unsplash

Accommodating the variable output from renewable generation in comparatively inflexible power systems designed around legacy thermal generation is the primary obstacle to power system decarbonization.

This is readily evident in China today, where as much as 16% of available wind power nationally has been curtailed (i.e., wasted due to grid constraints) in recent years, particularly in northern wind-rich provinces. This has prompted the government to suspend approval of many new wind farms in precisely the provinces where the potential is greatest until curtailment can be reduced. Curtailment has also

afflicted solar and hydro power production in recent years. These curtailments occurred while the renewable share of total power generated was still very far from the presumed 80-90%² needed to achieve carbon neutrality: around 10% was generated by wind and solar together in 2020, and 28% if hydro is also included.

The challenges of grid integration of renewable power, while critical to decarbonization, have not been adequately considered in studies to date of national pathways to carbon neutrality in China. Limited by data availability and modeling complexity, most studies consider only selective time periods (not the continuous 8760 hours of a year) and do not capture realistic limits

to operational flexibility of thermal power units. They also consider only limited transmission corridor possibilities and do not differentiate properties of AC and DC³ lines under different voltage levels. Nor do they adequately consider the effects of major new power demands such as power-to-gas (P2G) green hydrogen production and an electrified vehicle fleet. And they do not anticipate potential large-scale expansion of offshore wind in China.

To capture the many intricacies and tradeoffs in addressing the grid integration challenges of renewable expansion requires a uniquely comprehensive analytical platform. It requires a high-resolution assessment model considering not only renewable and thermal generation discussed above, but also hourly simulation of power system operations over an entire sample year and energy demands of other sectors including electrified transportation. It then must optimize investments in renewable generation, transmission, power storage, and P2G green hydrogen production on a province-by-province basis and calculate the costs of resulting carbon reductions. To understand more about the model, including an imbedded fast unit-commitment model to speed computations, interested readers are referred to the underlying peer-reviewed publication.⁴

² This assumes decarbonization of a remaining share of thermal power with carbon capture and storage or by offsetting it with negative carbon strategies.

³ Alternating current and direct current.

⁴ Chen et al., 2021, *ibid.*



Employing a conventional strategy replacing thermal generation with chiefly local solar and wind power would cause significant power balance challenges.

Key Results

The results indicate that despite renewable LCOEs that will be cost-competitive with thermal generation in critical provinces (Figure 1), achieving 80% decarbonization in 2050 employing a conventional strategy replacing thermal generation with chiefly local solar and wind power⁵ would cause significant power balance challenges.

To address these challenges would require additional investments in power storage—both utility-scale lithium batteries and pumped hydro where available—equivalent to a CO₂ abatement cost of around US\$27/ton compared to a business-as-usual (BAU) case without carbon constraints and only thermal power additions.

Adding deployment of an expanded ultra-high-voltage (UHV⁶) transmission network for grid interconnection and optimizing on a national—not provincial—scale could reduce this cost 63%

to US\$10/ton of CO₂, mainly by reducing investments in storage capacity to balance the power system by 50%. The total onshore wind, offshore wind, and solar capacities in 2050 would be 1700 GW, 900 GW, and 1350 GW, respectively, collectively more than three times the world's current cumulative solar and wind capacity.

A more comprehensive optimized strategy incorporating deployment of P2G green hydrogen production and slow-charged electric vehicles would turn the cost of 80% system decarbonization by 2050 negative compared to BAU, to US\$-25/ton. The benefit of replacing a grid integration strategy based on conventional assumptions with an optimized national-scale and cross-sector one is thus significant, saving roughly US\$52/ton of CO₂ abatement.

Such savings are sufficient to cover investment in costly CCS at all thermal power plants responsible for the remaining 20% of emissions, achieving a carbon neutral power system by 2050 at no net cost compared to BAU.



⁵ “Local” refers to sources available without expansion of existing transmission capacity, largely those within the same provinces.

⁶ 1000kV AC or 800kV DC

Image: Power grid by Yuan Yang / Unsplash

Geographical Distribution of Power Generation and Transmission

A geographical representation of the optimized generation and transmission structure for 80% decarbonization by 2050 is shown in **Figure 2**. Onshore wind capacity is unsurprisingly concentrated in the north (light green in the pie charts), offshore wind in the coastal east to southeast (dark green), and solar PV (orange) distributed throughout China except for north, northeast, and south-central provinces. A total of around 750 GW of new UHV transmission is deployed, accounting for roughly half of added transmission capacity. The optimization favors AC lines for connections of provinces within regional grids and DC lines for connections over greater distances, notably between regional grids.

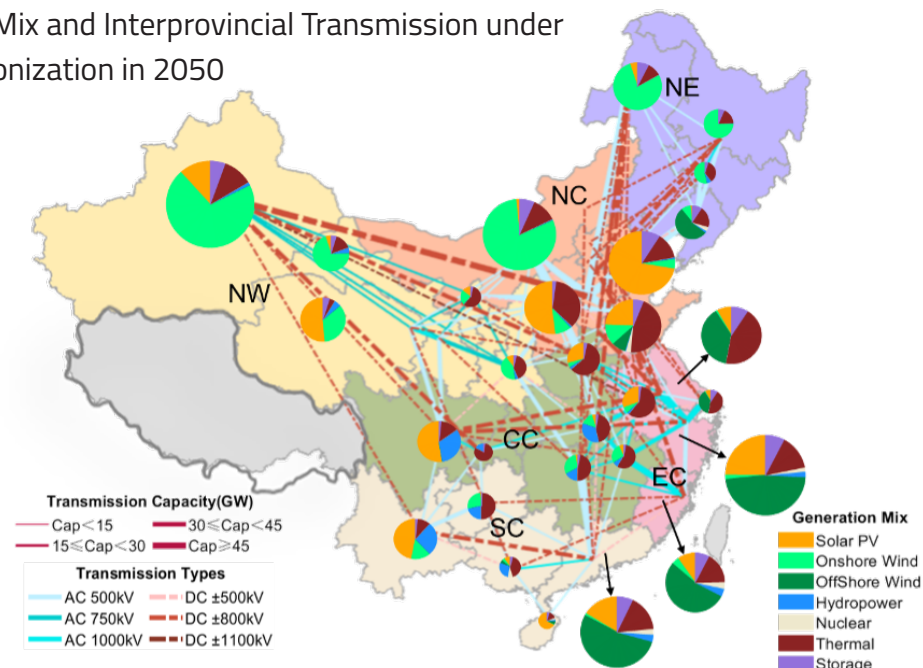
Offshore wind plays a more important role in a comprehensive strategy than previously recognized not only because of the growing size of its potential as its costs decline, but also because of its proximity to China's largest electricity demand centers on the coast.

This then also frees onshore wind power generated mainly in the interior north and solar power generated throughout much of the rest of China to serve more proximal demands. The resulting reduction of bulk electricity transfers over long distances reduces overall costs, even

accounting for new seabed transmission from extensive offshore wind developments.

Driven especially by the benefits of large-scale offshore wind in the east, the analysis portends a major shift in the national transmission planning paradigm from the conventionally assumed "West-to-East" one (prompted originally by hydro development in the southwest and later also onshore wind in the northwest) to a "Periphery-to-the-Center" one to achieve China's decarbonized future. This is illustrated by the larger generation capacities (and pie charts in **Figure 2**) in China's border and coastal provinces than in its interior ones.

Figure 2. Geographical Distribution of Optimal Provincial Generation Mix and Interprovincial Transmission under 80% Decarbonization in 2050



Benefits of Expanded UHV Transmission and Interconnection to Renewable Grid Integration



Electrical tower by Miguel Á. Padriñán / Pexel

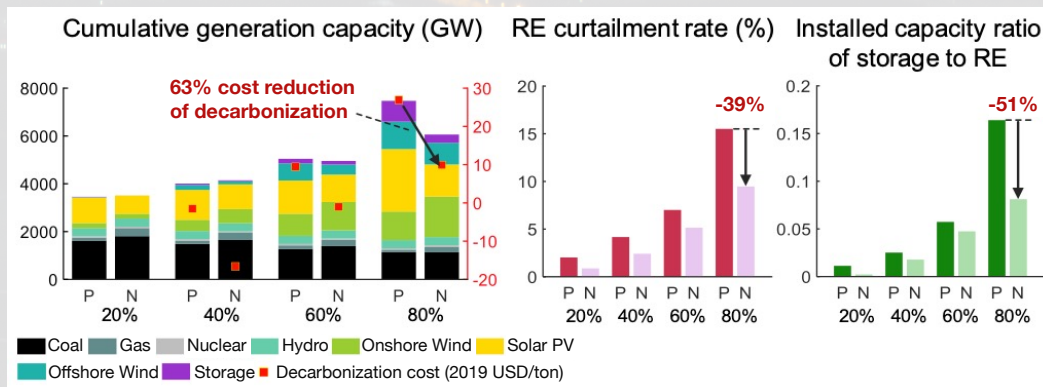
China has constructed large-scale UHV transmission networks to move large amounts of electricity, often DC lines to transmit with low line losses renewable power generated in the west and north over long distances to load centers in the east.

The effectiveness of the existing network has been debated within China. To evaluate the benefits of greater interconnection of power grids across China under massively expanded renewables, the study compares two scenarios: one relying on the limited existing interprovincial interconnections and optimizing generation and transmission for power balancing within provinces, and another that optimizes generation and new transmission lines across provinces to balance power nationally. The study considers both DC and AC options over a range of standard voltage levels, as well as feasible corridors for construction of new lines.

The benefits of national over provincial power balancing are striking, notably allowing regions with the greatest renewable resources (such

as northern China for onshore wind) to scale up generation much more significantly to supply other provinces. As shown in the middle and right panels of **Figure 3** for the 80% renewable power share—including wind, solar, hydro and nuclear⁷—the forced curtailment of renewable power under power balancing at the national level (labeled “N”) would decline 39% compared to the provincial balancing scenario (“P”) and the ratio of installed electricity storage to renewable power capacity would decline by more than half. The latter includes avoidance of up to 500 GW of storage capacity that would have to be built under provincial power balancing. This and other cost savings result in a 63% reduction of total system decarbonization costs, as shown in red on the left panel.

Figure 3. Benefits of Optimal Transmission for National vs. Provincial Power Balancing under 80% Decarbonization in 2050



⁷ Nuclear power is not renewable but is often categorized with renewables because nuclear generation does not emit CO₂.



Benefits of Power Storage, Green Hydrogen Production, and Slow Charging of Electric Vehicles to Renewable Grid Integration

Growing feasibility of large capacities of power storage, power-to-gas green hydrogen production, and electric vehicles (EVs) could all play major roles in easing grid integration and therefore lowering costs of a major expansion of renewable power generation in China.

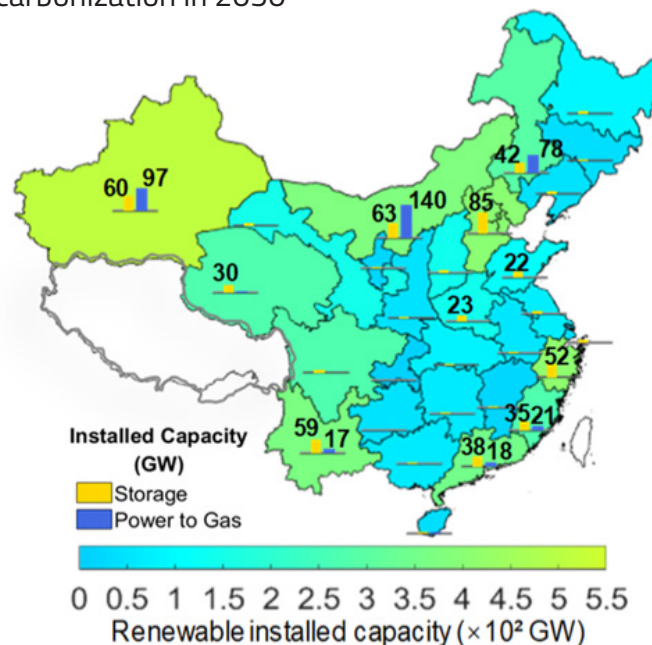
In the case of green hydrogen and EVs, the more flexible nature of their demands for electricity compared to the instantaneous nature of most conventional power loads are especially valuable in addressing the central challenge to the grid of balancing demand with supply from a generation mix increasingly dominated by variable sources (i.e., solar and wind).

Power Storage. Storing electricity is the simplest and most intuitive way to accommodate the variability of renewable power generation by the grid. The limitation is its cost, particularly at scale. Pumped hydro⁸ is relatively inexpensive but is constrained by topography and has limited growth prospects in China. Utility-scale lithium battery systems are growing in use in China and around the world, but deployment remains modest because of costs.

While high, however, those costs are quickly declining. The study tests a range of projections of reductions of costs for battery storage based on international forecasts. When applying a projection of relatively strong cost decline to 2050, the results indicate that every 10% reduction in storage cost would save China approximately US\$4 billion in grid

integration costs to reach an 80% decarbonized power system in 2050. A 50% cost reduction by 2050 would decrease overall costs of CO₂ abatement by 30%. Even then, storage would remain a comparatively expensive way to offset renewable variability and would be employed only when less costly power balancing options are unavailable.

Figure 4. Geographical Distribution of Power Storage and P2G Green Hydrogen Production Capacities under 80% Decarbonization in 2050



⁸ Pumped hydro is a proven technology used for decades around the world, mainly at small scale. When electricity is in surplus and inexpensive, it is used to pump water uphill to a reservoir. The water is then released during times of high demand to generate power in a conventional hydropower turbine.

⁹ This refers to production from iron ore, not recycling of steel scrap using electric arc furnaces.

P2G Green Hydrogen Production. Green hydrogen is produced by electrolysis of water using renewable power, a process also known as power-to-gas or P2G. Green hydrogen provides potential energy options to decarbonize processes for which direct electrification is difficult, notably high-temperature industrial production of iron & steel⁹, cement, and chemicals, and heavy-duty transport modes including long-distance trucking, shipping, and aviation. It can also serve as a chemical feedstock and reductant, replacing those derived from fossil fuels. The study takes the projections of China's Hydrogen Alliance of 60 million tons of hydrogen demand for industrial and transportation uses in 2050, and then includes optimized investment in and provincial siting of green hydrogen plants to supply this demand in a way that also cost-effectively serves the needs of balancing variability of expanded renewables. Inclusion of green hydrogen production in a comprehensive strategy again reduces total costs of CO₂ abatement.

Figure 4 illustrates the geographical distribution of installed capacities of renewable power, storage, and P2G green hydrogen production under the comprehensive strategy to achieve 80% decarbonized electricity by 2050. The color shading of the provinces reflects the total installed capacities of renewables (in 100s of GW), concentrated in provinces shaded yellow-green to green throughout China's border and coastal periphery. Yellow bars represent total power storage capacities (in GW), with values specified for provinces with more than 20 GW of storage, and blue bars P2G hydrogen production (in GW) with values indicated where greater than 5 GW. The co-location of large renewable capacities with large capacities of storage and P2G hydrogen production highlights the cost-minimized load-balancing benefits of the latter in decarbonizing China's power sector using renewable sources.

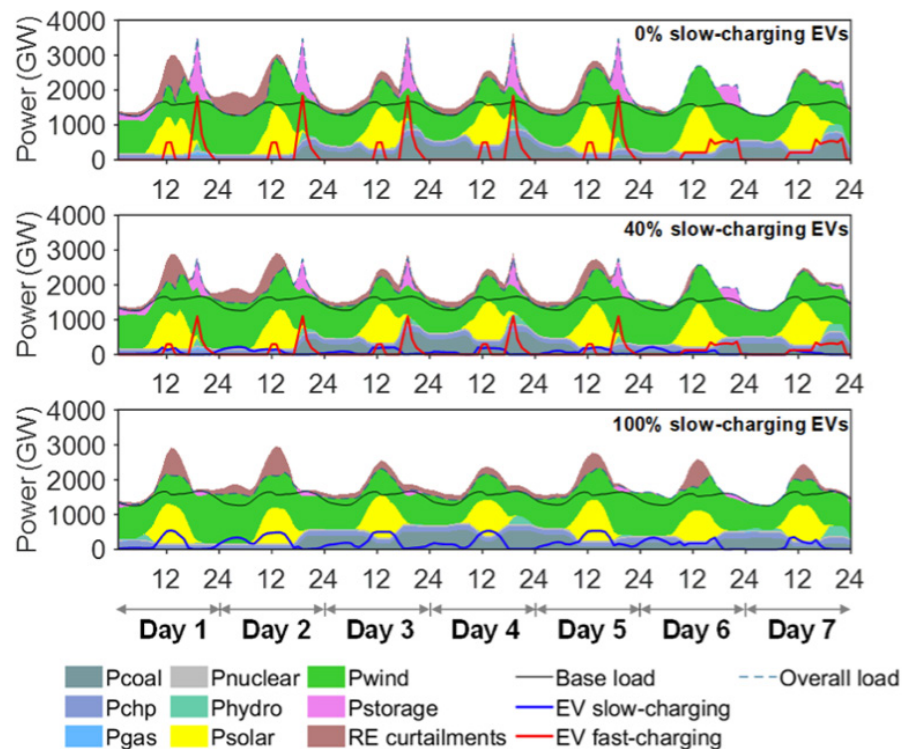
Slow Charging of Electric Vehicles. With as many as 380 million light-duty EVs projected in China by 2050, transportation will grow into a significant com-

ponent of electricity demand. How that demand affects—or even potentially benefits—a decarbonized power system depends significantly on the charging strategy, because that strategy in turn will affect the timing of the new demand. A key consideration is typical time-activity patterns of drivers: if EVs are fast-charged at charging stations (akin to current fuel stations), drivers will naturally tend to stop for charging when already driving their cars. But if those drivers display similar time-of-day driving patterns, it will lead to spikes in electricity demand that are difficult for the power system to accommodate without more storage capacity. If EVs are instead slow-charged (chiefly at homes or workplaces), it will spread the resulting power demand and allow the system to schedule it at times advantageous for balancing the inherent variations of the renewable power supply.

To examine these tradeoffs, the study simulates the charging demand for individual EVs according to probabilistic driving behavior and vehicle charge characteristics at 15-minute intervals. It then aggregates them into hourly collective charging demand for each province and the country. **Figure 5**

represents the cost-minimized hourly dispatch of electricity—including demand (load), supply by source, and forced curtailment—totaled over China during a representative week from Monday through Sunday, under the comprehensive strategy to achieve 80% decarbonized power generation by 2050. The top panel shows a system where all EVs are fast-charged (collective power demand denoted by a red line), the bottom one a system where they are all slow-charged (blue line), and the middle panel a system with 60% fast and 40% slow charging. The top figure highlights that 100% fast-charging of EVs will create spikes in demand during the workday rush hour at 7 PM (hour 19 on a 0-24 scale) that the power system can best accommodate by insuring more storage is available (pink areas). As the bottom figure shows, 100% slow charging avoids severe spikes in demand and therefore the additional investment in power storage. Slow charging also necessitates somewhat more curtailment over the week, but the net effect is less expensive accommodation of renewable power variation, which in turn reduces the cost of CO₂ reduction.

Figure 5. Hourly National Power Balances with a Fast- vs. Slow-Charged Electric Vehicle Fleet





Lessons for Other Countries

While the study focuses on China, many of the challenges are common to other high-emitting industrial economies and the varied elements of a comprehensive grid-integration strategy are likely to benefit them similarly.

These countries too must massively expand solar and onshore wind generation to decarbonize their power

systems, and many of them—including the U.S.—will be able to develop large offshore wind resources located close to urban load centers in coastal regions. They too would benefit from greater interconnection of regional grids using expanded UHV transmission. Storage is likely to play similar roles in their power systems, as its costs decline. And they are also likely to develop large and more flexible types of power demand, including green hydrogen production to decar-

bonize hard-to-abate industrial and transport sectors and large EV fleets in which slow charging may offer similar benefits for power balancing over fast charging. The overall effects of comprehensive grid-integration strategies to decarbonize power systems will differ by country, but such strategies are likely to reduce costs compared to narrower, more conventional approaches everywhere.

HUAZHONG UNIVERSITY OF SCIENCE AND TECHNOLOGY

State Key Laboratory of Advanced Electromagnetic Engineering and Technology
School of Electrical and Electronic Engineering, Wuhan, China

HARVARD UNIVERSITY

Harvard-China Project on Energy, Economy and Environment
Harvard John A. Paulson School of Engineering and Applied Sciences, Cambridge, MA, USA

TSINGHUA UNIVERSITY

Department of Electrical Engineering, Beijing, China

