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Green Hydrogen from Expanded Wind Power in China:

Reducing Costs of Deep Decarbonization

A Research Brief for Non-Specialists of a Recent Study Published in *Renewable Energy*

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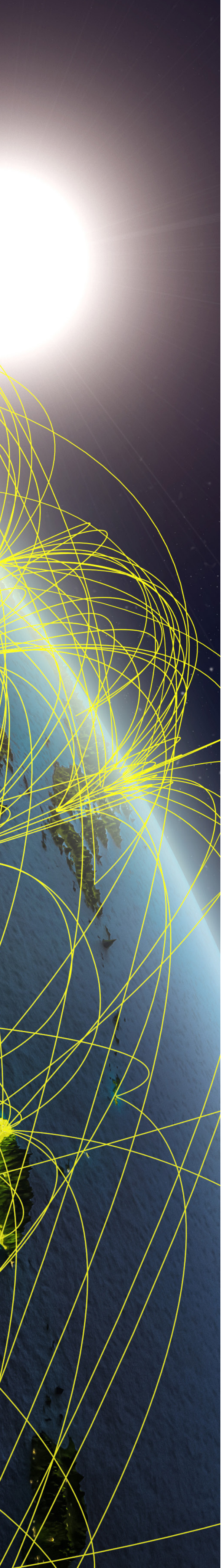

Acknowledgements

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

> Haiyang Lin, Qiuwei Wu, Xinyu Chen, Xi Yang, Xinyang Guo, Jiajun Lv, Tianguang Lu, Shaojie Song, and Michael B. McElroy. 2021. "Economic and technological feasibility of using power-to-hydrogen technology under higher wind penetration in China." *Renewable Energy*, 173, 569-580. Available at https://doi.org/10.1016/j.renene.2021.04.015.

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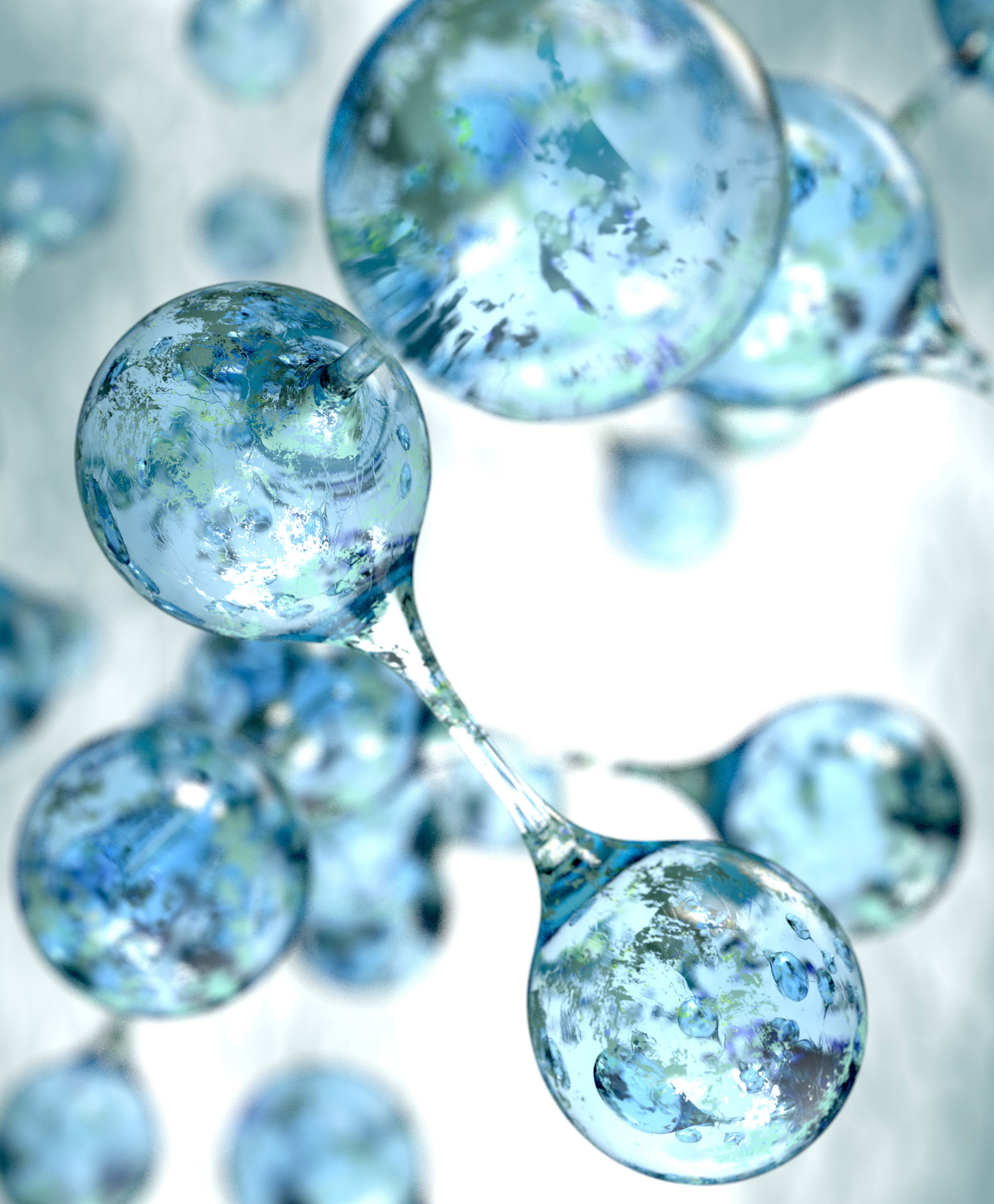


Key Takeaways

Wind Power in China

- China leads the world in wind power generation, with 61% of its onshore wind capacity located in windy northern regions.
- Northern China's power systems are nevertheless still dominated by coal-fired power plants. Integration of growing shares of variable wind electricity into power systems designed around inflexible coal generation poses difficult challenges for power balancing and grid operations.
- Exacerbating this difficulty, northern China is also cold, especially in winter. Most of its building heating is provided by coal-fired combined heat and power (CHP) plants, forced into particularly inflexible "must-run" status. The result is high wind power curtailment, in which inexpensive and zero-carbon electricity is wasted because the power system must favor more costly and carbon-emitting coal-fired power to provide heat.

Hydrogen in China

- Hydrogen is a major chemical feedstock in China. It is currently produced from coal, termed "black" hydrogen, with high CO_2 emissions.
- "Green" hydrogen is produced from water using electrolysis powered by renewable energy, without CO_2 emissions. Its production can be scheduled to accommodate variations in wind power generation.
- If costs of green hydrogen become competitive, it can reduce CO_2 emissions both by replacing black hydrogen as an industrial feedstock and as an alternative energy source for key industries and transportation modes now fueled by fossil sources.

Western Inner Mongolia (WIM) is representative of northern China and an advantageous location for production and use of green hydrogen because of its high wind power generation and potentials as well as its existing coal-based production of electricity, heat, and black hydrogen.

Green hydrogen produced from wind power is competitive with black hydrogen in WIM, with large production levels possible at less than US$2/kg, a widely accepted threshold for cost-competitiveness with black hydrogen.

As important are the additional benefits of green hydrogen production in terms of reduced wind curtailment—even at expanded wind power capacities—and reduced CO_2 emissions. If WIM expands to 50 GW of wind capacity in 2030 (from 18 GW in 2018), maximizing production of all green hydrogen costing less than US$2/kg to replace black hydrogen would reduce about 100 million tons of CO_2 emissions per year.

The cost of green hydrogen production is expected to decrease further over the next decade, due to increases in wind power capacity and declining costs of electrolyzer technologies.

Source Article: Haiyang Lin, Qiuwei Wu, Xinyu Chen, Xi Yang, Xinyang Guo, Jiajun Lv, Tianguang Lu, Shaojie Song, and Michael B. McElroy. 2021. "Economic and technological feasibility of using power-to-hydrogen technology under higher wind penetration in China." *Renewable Energy*, 173, 569-580. Available at https://doi.org/10.1016/j.renene.2021.04.015.

Wind Power in Northern China

China leads the world in wind power generation, with 281 GW of installed capacity at the end of 2020 and swift expansion planned to help meet its goals of peak carbon before 2030 and carbon neutrality by 2060.

Integration of variable renewable (wind and solar) electricity into a power system designed around inflexible coal-fired generation, however, poses enormous challenges for power balancing and grid operations. This could become more difficult as the renewable share of generation rises over time.

Northern China[1] is of particular interest. Much of it is windy and it currently hosts 61% of China's onshore wind capacity. But it is also rich in coal and its power systems are still dominated by coal-fired power plants. Those plants include especially inflexible combined heat and power (CHP) units, which must often generate electricity in winter even when carbon-free and nearly costless wind power is in surplus, to provide heat for buildings.

The result in northern China is high curtailment of wind power, wasted because the power system cannot accommodate it. The national wind curtailment rate reached 21% in 2016, and the central government has suspended permits for construction of new wind farms in provinces with high curtailment, precisely China's areas of greatest wind potential.

Hydrogen in China

China is the world's largest producer of hydrogen, an industrial feedstock consumed mainly by the chemical industry, to produce ammonia-based fertilizer and methanol, and in petroleum refining.

It is now overwhelmingly produced in China from coal, termed "black" hydrogen, which averages 18.9 tons of CO_2 per ton of produced hydrogen and is thus a major industrial source of CO_2 emissions.

"Green" hydrogen is produced from water using electrolysis powered by renewable electricity, with zero CO_2 emissions. This process is also known as "Power-to-Hydrogen" (P2H) or "Power-to-Gas" (P2G). Electrolysis uses electricity to split molecules of water (H_2O) into hydrogen and oxygen molecules in separate gas streams. It is accomplished by devices called electrolyzers, with three main technologies known by their acronyms: AEC, PEMEC, and SOEC.[4] AEC is the most mature and widespread, with low capital costs and high reliability but relatively poor conversion efficiency. PEMEC is more efficient and can produce compressed gases, an advantage for hydrogen storage, but it requires expensive membranes and platinum catalysts. SOEC is newer and less proven but has the highest efficiency and is considered the most promising and cost-effective electrolyzer technology for the future.

If costs of electrolytic green hydrogen become competitive, it could reduce CO_2 emissions by immediately replacing black hydrogen as a chemical feedstock. It has even larger decarbonizing potential as a carbon-free alternative energy source in major coal-consuming industrial sectors that are difficult to electrify because they require high temperatures, such as iron & steel and cement production, and in petroleum-fueled heavy-duty transport, including long-distance trucking, shipping, and aviation.

1 Northern China refers to Northwest, North, and Northeast regions as traditionally defined, stretching along the border from Xinjiang to Heilongjiang and down to Qinghai, Gansu, Shaanxi, Shanxi, Hebei, and Shandong.

2 It is sometimes called "brown" hydrogen if derived from lignite, lower-quality "brown" coal. "Grey" hydrogen, more common in western countries, is produced from natural gas.

3 The oxygen gas stream also has economic value, but it is small compared to that of hydrogen.

4 Alkaline electrolytic cells, proton exchange electrolytic cells, and solid oxide electrolytic cells.

Research Goal

“THE OBJECTIVE IS TO TAKE ADVANTAGE OF WIND ENERGY TO PRODUCE CARBON-FREE GREEN HYDROGEN TO MEET INDUSTRIAL HYDROGEN DEMAND AT A COST LOWER THAN THAT OF COAL-DERIVED BLACK HYDROGEN”

The new study summarized in this Research Brief (Lin et al., published in *Renewable Energy*[5]) estimates the technical and economic feasibility of producing green hydrogen using wind power in China in the year 2030, focusing on Western Inner Mongolia (WIM) as a representative region.

The objective is to take advantage of wind energy to produce carbon-free green hydrogen to meet industrial demand at a cost lower than that of coal-derived black hydrogen. If green hydrogen can prove cost-competitive for serving existing industrial demands, it invites expanded investigation into its viability to also displace fossil fuels in crucial “hard-to-abate” industrial and transport sectors, a much larger and potentially transformative step towards China’s 2060 carbon neutrality goal.

The study utilizes an integrated power and heat optimization model developed earlier by the same team[6] to simulate the power system on an hourly basis to estimate on-grid additions of wind power and curtailment. That model then provides inputs into a newly developed electrolytic hydrogen production model to estimate its minimized costs. Driving the model are real-world data inputs, such as meteorological observations assimilated by NASA to estimate both wind power potentials and winter heating demand. Full explanation of the modeling structure and assumptions is beyond the scope of this summary for non-specialists, and interested readers are referred to the journal article.[7]

[5] Haiyang Lin, Qiuwei Wu, Xinyu Chen, Xi Yang, Xinyang Guo, Jiajun Lv, Tianguang Lu, Shaojie Song, and Michael B. McElroy. 2021. “Economic and technological feasibility of using power-to-hydrogen technology under higher wind penetration in China.” *Renewable Energy*, 173, 569-580, doi.org/10.1016/j.renene.2021.04.015.

[6] X.Y. Chen, J.J. Lv, M.B. McElroy, X.N. Han, C.P. Nielsen, and J.Y. Wen, 2018, *IEEE Transactions on Power Systems*, 33, 6, 6240-6253, doi.org/10.1109/tpwrs.2018.2827003; and X.Y. Chen, M.B. McElroy, and C.Q. Kang, 2018, *IEEE Transactions on Power Systems*, 33, 2, 1309-1319, doi.org/10.1109/tpwrs.2017.2736943.

[7] Lin et al. 2021, above.

Page 6 top image: Adobe photo by Hu. Page 6 lower image: Adobe photo by Shawn Hempel. Page 7 right image: Wind farms on the grassland of Huitengxile, Inner Mongolia, China | Adobe photo.

"THE REGION'S COAL, WIND AND HEATING DEMAND RAISE CHALLENGES AND OPPORTUNITIES FOR PRODUCTION OF GREEN HYDROGEN"

Energy Conditions of Western Inner Mongolia

WIM is representative of northern China, with a power mix in 2018 dominated by coal-fired plants (31 GW conventional and 21.5 GW CHP) and wind capacity (18.2 GW).

It is also cold, with a winter heating season of around 180 days per year that forces coal-fired CHP plants into "must-run" status to provide heat. The capacity of the WIM power grid to integrate its large wind power production is thus constrained, leading to high levels of curtailment. The region's combination of coal, wind, and heating demand together raise challenges as well as opportunities for production of green hydrogen, which may help to reduce wind curtailment, increase wind shares of total power generation, and reduce CO_2 emissions.

Figure 1 illustrates time patterns of electricity demand (in blue), heating demand (red), and wind power production (green) for WIM through the 8760 hours of 2018, from January to December. Electricity demand shows consistent short-term variations reflecting time-of-day changes and modest seasonal reduction in fall and early winter; heating demand varies seasonally, peaking in the coldest months and absent in the warmest ones; and wind power variations reflect changes in weather systems, seasonal differences (lower on average in summer due to regional climatology), and daily changes due to typically stronger winds at night.

To show the growing risks of curtailment with expanding wind power, **Figure 2** illustrates projected daily variation of wind generation, including the share that can be integrated into the grid (light green) and the share that must be curtailed (dark green) for January 1-December 31 of 2030, under different levels of possible wind deployment: 20 GW (close to the current level), 50 GW, and 100 GW.[8] Curtailment is clearly concentrated in colder months, and increases with greater wind power capacities. The share of total annual generation curtailed at 50 GW of wind capacity would be 8.1% of all available wind power, slightly less than the 2018 level of 10.2%. It would explode to 42.8%, however, if WIM instead had 100 GW of capacity, in the absence of new ways to utilize the excess wind. Among such options is green hydrogen production.

[8] The projection is based on meteorological data for a typical recent year, as daily wind variation cannot be predicted for 2030.

Figure 1. Hourly Electricity Demand, Heat Demand, and Wind Power Supply during 2018 in Western Inner Mongolia

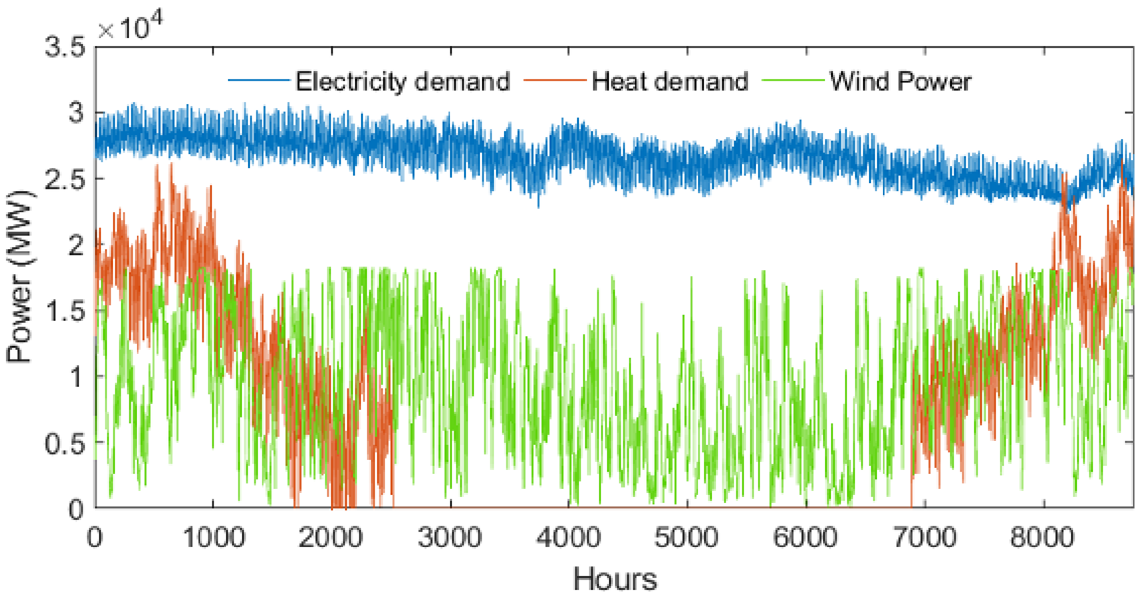
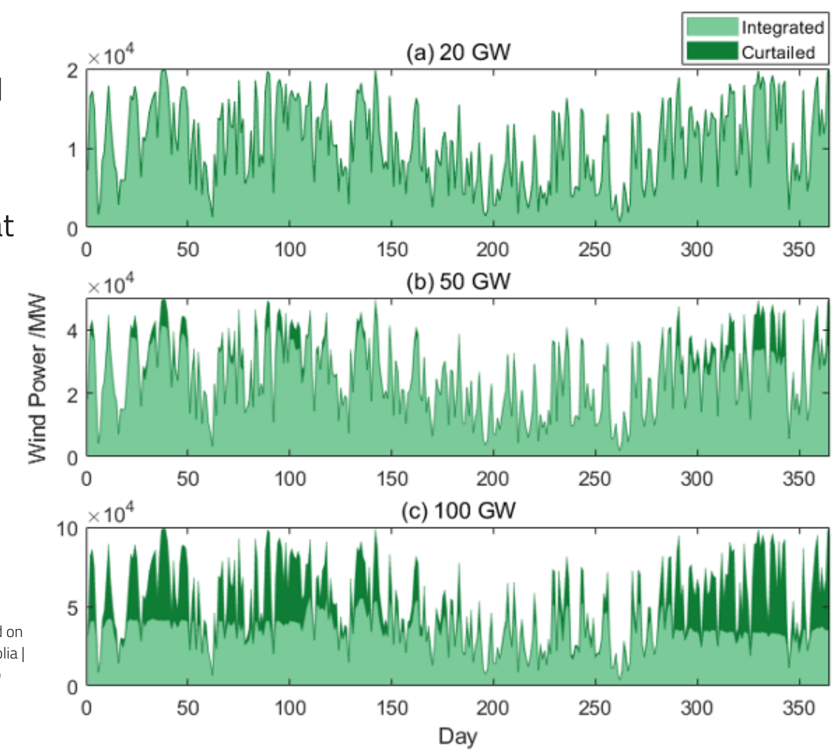


Figure 2. Daily Wind Power Supply and Curtailment in WIM Projected in 2030, at Different Installed Wind Capacities



Left Image: A field of wind turbines build on a vast pasture in Xilinhot in Inner Mongolia | Adobe photo. Right image: Adobe Photo

Costs of Hydrogen Produced from Wind in Western Inner Mongolia

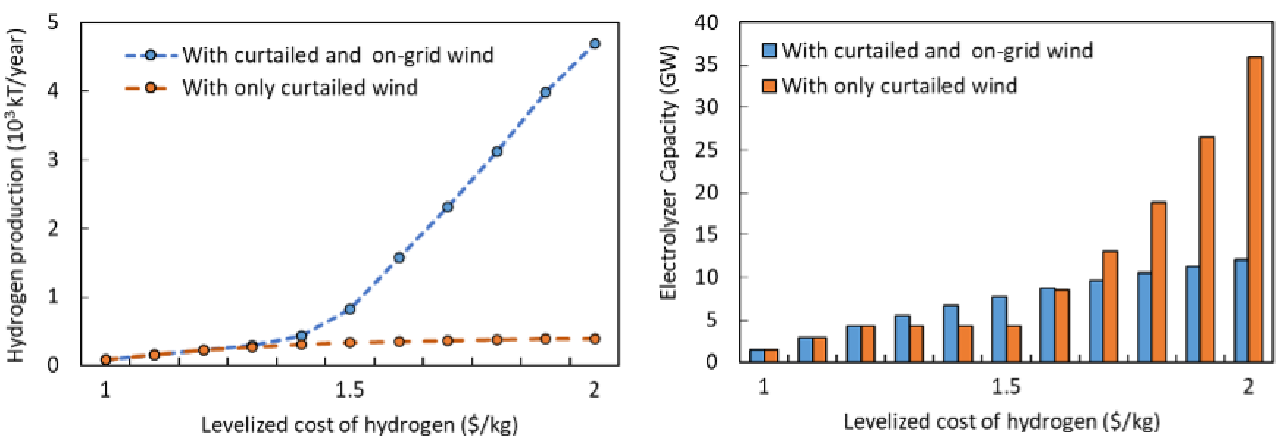
The left panel of **Figure 3** illustrates the quantities of green hydrogen that can be produced at different levelized costs of hydrogen (LCOH) for the WIM power system in 2030. It assumes 50 GW of installed capacity of wind power (yielding a curtailment rate similar to that of today) and deployment of SOEC electrolyzers, projected to be the least costly option in 2030. Note that the net industrial hydrogen demand in WIM was 692 kilotons/year in 2018 and is projected to reach 950 kilotons/year in 2030, a level just below the 1 on the y-axis of the figure (expressed in 1000s of kilotons). Current demand is met with black hydrogen at a cost of around US$1.48/kg.

Focusing first on hydrogen produced only with curtailed power (the orange line in the left panel of **Figure 3**), it will be very inexpensive at relatively low levels of production because the process can exploit curtailed wind power that is otherwise wasted and thus costless. This is true as long as curtailed wind power is abundant enough to operate electrolyzers sufficiently to spread their investment costs. More green hydrogen can be produced from additional curtailed wind power but at slowly rising costs, because the most consistently available curtailed wind will have already been exploited. As a result, the duty cycles of electrolyzers—the percentage of time they can operate—will decline, and with them the ability to spread investment costs.

Electrolyzers can produce hydrogen with any source of electricity, however, not just curtailed wind power. An important finding of the paper is represented by the blue line in the left panel of **Figure 3**, in which wind power successfully integrated into the grid is also made available to the hydrogen production system. Use of on-grid wind power will significantly enhance total hydrogen production at any cost level above US$1.4/kg. This may seem surprising given that on-grid power must be purchased—while curtailed wind power is free—but it results from more continuous operation of electrolyzers using on-grid power and thus more efficient use of the associated capital investment. This is further explained in the right panel of **Figure 3**. It illustrates that adding access also to on-grid wind power allows electrolyzers to become increasingly productive at costs above US$1.4/kg, to the extent that far less total capacity (i.e., fewer systems) would be needed to produce far more green hydrogen if there is market demand at US$2/kg.

Such productive capacity could come into play to provide zero-carbon energy inputs for major hard-to-abate industrial and transportation sectors, as introduced above, a central challenge in China's path to carbon neutrality. Assuming 50 GW of wind capacity in 2030, the maximum amounts of hydrogen that could be produced at less than US$2/kg would help reduce about 100 MT of CO_2 emissions per year, approximately half of the annual carbon footprint of Beijing. To serve the more modest projected demand for hydrogen as conventional industrial feedstocks in 2030, 950 kilotons of green hydrogen could be produced from a combination of on-grid and otherwise-curtailed wind power at a cost of US$1.52/kg.

Figure 3. Green Hydrogen Production and Electrolyzer Capacities at Different Costs (Assuming 50 GW Wind Capacity in WIM in 2030)



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