Potential for Wind-Generated Electricity in China
Michael B. McElroy, *et al.*
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Potential for Wind-Generated Electricity in China

Michael B. McElroy,[1]*† Xi Lu,[2]* Chris P. Nielsen,[3] Yuxuan Wang[4]

Wind offers an important alternative to coal as a source of energy for generation of electricity in China with the potential for substantial savings in carbon dioxide emissions. Wind fields derived from assimilated meteorological data are used to assess the potential for wind-generated electricity in China subject to the existing government-approved bidding process for new wind farms. Assuming a guaranteed price of 0.516 RMB (7.6 U.S. cents) per kilowatt-hour for delivery of electricity to the grid over an agreed initial average period of 10 years, it is concluded that wind could accommodate all of the demand for electricity projected for 2030, about twice current consumption. Electricity available at a concession price as low as 0.4 RMB per kilowatt-hour would be sufficient to displace 23% of electricity generated from coal.

Demand for electricity in China is increasing at an annual rate of ~10%. The current installed Chinese national power-generating capacity (792.5 GW) is second only to that of the United States (1032 GW). Combustion of coal accounts for ~80% of total electricity production. Wind, with an installed capacity of 12.2 GW at the end of 2008, is currently a minor contributor to China's total electricity supply (0.4%). Most studies suggest that coal will continue to provide the dominant source of electricity in China for the foreseeable future and that China's emissions of CO_2 are likely to grow accordingly (China is now the world's largest emitter of CO_2, having surpassed the United States in mid-2006). Here, we estimate the potential for wind as an economically competitive alternative to coal in China's energy future.

Development of renewable energy in China received an important boost with passage of the Renewable Energy Law in 2005. Wind projects larger than 50 MW are authorized under a concession bidding process managed by the National Development and Reform Commission (NDRC) (*1*). Concessions are allocated typically for a 25-year period in regions preselected by the NDRC. Provincial grid companies are required to sign a power purchase agreement (PPA) with successful bidders. The price at which electricity is delivered to the grid is fixed during an initial period, typically about 10 years, at a level set during the initial bidding process. The price in subsequent years is expected to adjust to the prevailing electricity market price in the region served by the grid.

Investments in renewable energy benefit from favorable treatment both in terms of obligations for value added tax (VAT) and enterprise income tax (EIT). Plans approved by NDRC typically allow for an internal rate of return on investment of about 10% per year. Projects are approved commonly on the basis of 20% equity and 80% debt, the latter financed typically at an interest rate of 6.2% per year.

The objective of this study is to estimate the quantity of electricity that could be generated from wind and delivered profitably to the grid under the bidding and financial conditions currently in place in China. For bidders, the key quantity relates to the price proposed for the supply of electricity to the grid during the initial fixed price period. The greater the electricity that can be produced by installation of turbines of a specified power rating, the lower the initial bidding price for which a project may be projected as economically feasible (*2*).

Wind resources are evaluated in this study using a database from Version 5 of the Goddard Earth Observing System Data Assimilation System (GEOS-5 DAS) (*3*). Winds included in this compilation were obtained by retrospective analysis of global meteorological data with a state-of-the-art weather/climate model incorporating inputs from a diverse suite of measurements taken worldwide from a combination of surface observations, aircraft, balloons, ships, buoys, and satellites. Data are available with a temporal resolution of 6 hours and a spatial resolution of 0.5° longitude by 0.67° latitude (~50 km by 66.7 km at mid-latitudes). To account for the interannual variability in wind speeds, the study made use of assimilation data for the 5-year interval 2004 to 2008. We estimated specifically the electricity that could be generated with a distributed set of land-based GE 1.5MW xle turbines (*4*). Hub height for these turbines is 80 m; rotor diameters measure 82.5 m (*5*). In assessing potential land-based wind resources, we elected, following Lu *et al.* (*6*), to exclude forested areas, areas occupied by permanent snow or ice, areas covered by water, and areas identified as either developed or urban. We also excluded land areas with slopes greater than 20% (*7*).

The spatial distribution of capacity factors (CFs) (*8*) evaluated for deployment of the 1.5-MW turbines considered here is illustrated in Fig. 1. Wind conditions are notably favorable, and CF values are consequently large, over extensive regions of north China (Inner Mongolia, Heilongjiang, Jilin, and Liaoning) and in parts of the west (Tibet, Xinjiang, Qinghai, and Gansu). Wind farms deployed recently in the United States have achieved operational CFs as high as 48%, with an average of ~35% (*9*). In comparison, CFs for wind farms installed in China have been substantially lower than for the United States, ~23% on average (*10*). The relatively low operational performance for wind farms in China as compared to the United States is attributed (*10*, *11*) to a combination of factors: intrinsically lower wind speeds for China; lower quality of the largely domestically produced turbines deployed in China as compared with turbines available on the international market; bottlenecks introduced by limitations imposed by the existing Chinese electricity grid; and suboptimal siting of wind farms due to inadequate prior screening of potentially available wind resources.

Electricity that could be generated from wind irrespective of price—restricted, however, to installations capable of operating with CFs greater than 20%—is illustrated for the existing seven electric grid areas of China in Fig. 2. The figure also includes results expressed as ratios with respect to the

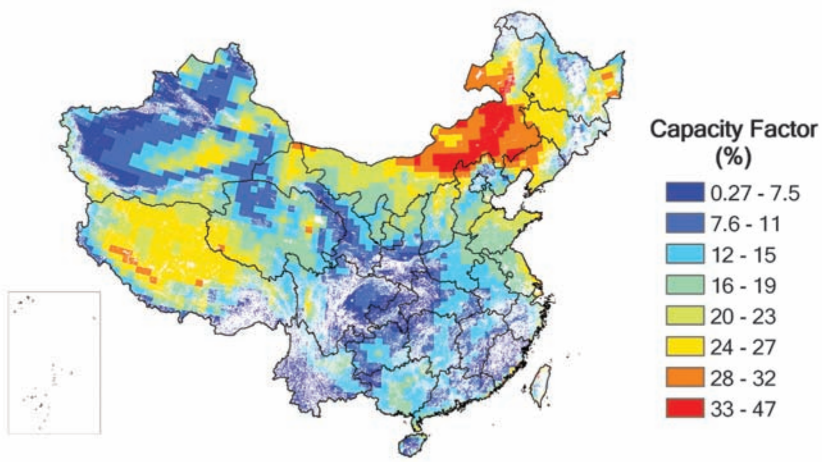


Fig. 1. Spatial distribution of capacity factors evaluated for deployment of the 1.5-MW turbines.

[1]School of Engineering and Applied Science and Department of Earth and Planetary Sciences, Harvard University, Cambridge, MA 02138, USA. [2]School of Engineering and Applied Science, Harvard University, Cambridge, MA 02138, USA. [3]Harvard China Project and School of Engineering and Applied Sciences, Harvard University, Cambridge, MA 02138, USA. [4]Department of Environmental Science and Engineering, Tsinghua University, Beijing, China.

*These authors contributed equally to this work.
†To whom correspondence should be addressed. E-mail: mbm@seas.harvard.edu

current production of electricity in these grid regions. The data displayed here suggest that a suite of 1.5-MW turbines deployed in onshore regions with favorable wind resources could provide potentially as much as 24.7 PWh of electricity annually, more than seven times current national consumption.

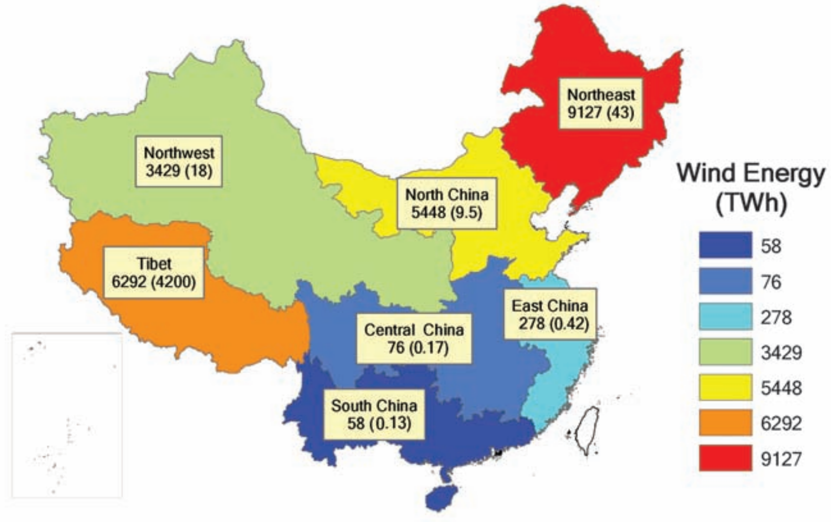


Fig. 2. Potential electricity irrespective of price that could be generated over seven electric grid areas of China mainland. The values in parentheses are the ratios of potential wind-generated electricity to current electricity production in each grid area.

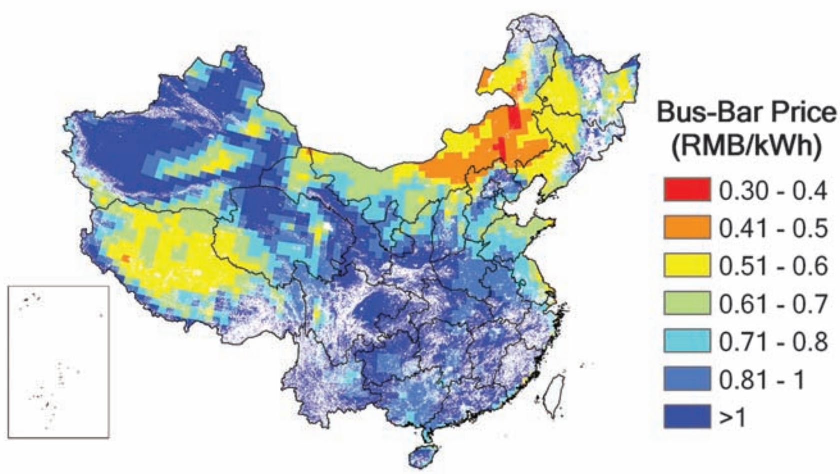
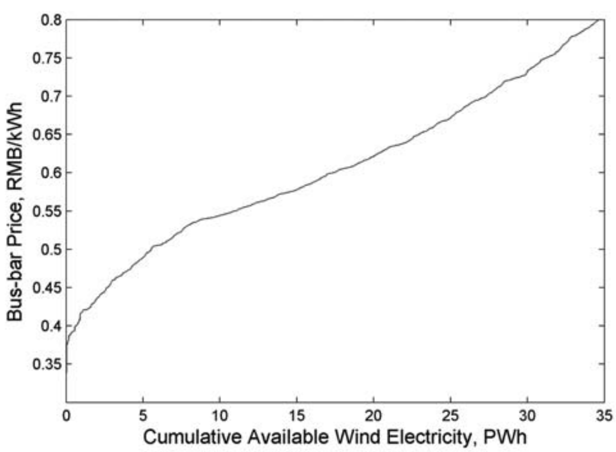


Fig. 3. Geographic distribution of bus-bar prices for economically viable wind investments.

Fig. 4. Potential electricity that could be generated nationally as a function of bus-bar concession price.



The geographic distribution of prices at which wind-generated electricity could be delivered profitably to the grid (so-called bus-bar prices) is illustrated in Fig. 3. Prices contracted for recently approved concession projects have ranged from 0.382 to 0.551 RMB/kWh (*12*). The electricity that could be generated profitably from onshore wind farms on a national basis is illustrated as a function of the assumed grid-delivered concession price in Fig. 4. The analysis summarized here [outlined in more detail in the supporting online material (SOM), which includes also a discussion of the sensitivity of results to the specific assumptions adopted with respect to pricing] implies that at a contract price of 0.516 RMB/kWh, wind could accommodate an annual source of electricity as large as 6.96 PWh, more than twice current consumption (3.4 PWh), comparable to total demand projected for 2030 (*2*, *13*). A summary of current and potential future sources of electricity for the seven provinces identified to receive highest priority for future investments in wind energy by the Chinese Government is presented in table S1.

Current Chinese policy, as elaborated in the 11th Five Year Plan, targets a reduction in the energy intensity of the Chinese economy of 20% together with a reduction of 10% in emissions of sulfur between 2006 and 2010. To accomplish these objectives, NDRC has taken steps to eliminate large numbers of highly polluting, coal-fired power plants with capacities less than 50 MW, replacing them with more efficient larger coal-fired plants equipped to reduce not only emissions of sulfur but also emissions of particulate matter (plants with capacities greater than 300 MW). These steps are expected to result in a modest decrease in the rate of growth in future emissions of CO_2 from China. Generation of 1 MWh of electricity from coal with current technology is associated with emission of ~1 metric ton of CO_2 (*14*). Much larger reductions in CO_2 could be achieved by aggressive steps to substitute wind and other carbon-free sources of energy for coal in future planning for the Chinese power sector.

The present analysis suggests that the electricity that could be generated economically from wind at a grid-delivered contract price as low as 0.4 RBM/kWh, 0.62 PWh per year, could result in savings of CO_2 emissions by as much as 0.62 gigatons of CO_2 per year, equal to 9.4% of total current annual Chinese emissions of 6.6 gigatons of CO_2 per year (*15*). At a concession price of 0.516 RMB/kWh, this suggests that it would be possible to eliminate much if not all of the CO_2 expected to be emitted by the power sector over the foreseeable future. This would require a major investment of resources and could be accomplished only on the basis of a carefully designed long-range plan for the Chinese power sector. Benefits in terms of improvements in Chinese air quality would be substantial, however, and there could be important benefits also for the Chinese economy. The value of health damages associated with air pollution has been estimated at 0.7 to

4.3% of Chinese gross domestic product (GDP) (*16*). There would be obvious benefits also in moderating the pace of projected future changes in global climate. If 30% of additional electricity required by 2030 were produced from wind rather than coal (*13*), an ambitious but not unreasonable target, savings in CO_2 would amount to as much as 1.1 gigatons of CO_2 per year.

The present analysis does not explicitly account for the cost required to connect China's potential future source of wind electricity to the existing grid. Under current arrangements, the cost of connecting new sources of wind-generated electricity is assigned to the grid companies to which this electricity is delivered. Grid companies are allowed to recover this extra cost and a portion of the additional expense for the renewable source by adjusting the price at which electricity is delivered to the companies' existing customer base. The grid companies have little incentive, however, to encourage large-scale development of wind power. They can adjust with relative ease to a minor input of electricity from wind (as indicated earlier, the current source amounts to less than 0.4% of China's total consumption). With inputs as large as those contemplated here, adjustment problems would be more serious.

Wind resources are variable both in time and space. Supplies of electricity from wind are not necessarily well matched, therefore, with demand. Limitations imposed by the temporal variability can be minimized to some extent by development of an integrated national electric grid. Incorporating base load sources of electricity from coal-fired power plants poses relatively minor problems for grid managers charged with matching supplies of electricity with demand. Adjusting to an important, intrinsically variable, supply such as that from wind will require a more complex, and consequently more costly, grid management protocol.

China is now the world's fastest growing market for wind power. It has consistently in recent years exceeded national targets for the development of this resource. With 12.2 GW of installed capacity at the end of 2008, it now ranks number four in the world, surpassed only by the United States, Germany, and Spain. Current policy calls for 100 GW of installed capacity by 2020. Given current trends, it is likely that this target may also prove conservative. Meeting the increased demand for electricity anticipated for China over the next 20 years will require construction of the equivalent of 800 GW of coal-fired power plants (*13*). If this additional electricity is supplied mainly by coal, emissions of CO_2 at the end of this period might be expected to increase by as much as 3.5 gigatons of CO_2 per year. To accommodate a reduction in emissions of 30%, exploiting the energy in wind rather than coal would require installation of ~640 GW of wind farms over this 20-year period, assuming that coal-fired power plants would operate at average CFs of 80% with wind farms functioning with average capacities of 30%. The present analysis suggests that wind resources in China could accommodate this target. This will require, however, a commitment by the Chinese government to an aggressive low-carbon energy future. Introducing 640 GW of wind capacity over a 20-year period at current prices would require an investment of ~6.0 trillion RMB (~900 billion U.S. dollars), assuming a 10 to 20% premium for grid connection, as suggested in (*7*). This is a large but not unreasonable investment given the present size of the Chinese economy (annual GDP of about 26 trillion RMB) and the scale of the investments in both generating capacity and the grid infrastructure that will be required in any event to accommodate anticipated future growth in power demand.

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Supporting Online Material

www.sciencemag.org/cgi/content/full/325/5946/1378/DC1
Materials and Methods
Fig. S1
Table S1
References

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Endogenous Nitric Oxide Protects Bacteria Against a Wide Spectrum of Antibiotics

Ivan Gusarov, Konstantin Shatalin, Marina Starodubtseva, Evgeny Nudler*

Bacterial nitric oxide synthases (bNOS) are present in many Gram-positive species and have been demonstrated to synthesize NO from arginine in vitro and in vivo. However, the physiological role of bNOS remains largely unknown. We show that NO generated by bNOS increases the resistance of bacteria to a broad spectrum of antibiotics, enabling the bacteria to survive and share habitats with antibiotic-producing microorganisms. NO-mediated resistance is achieved through both the chemical modification of toxic compounds and the alleviation of the oxidative stress imposed by many antibiotics. Our results suggest that the inhibition of NOS activity may increase the effectiveness of antimicrobial therapy.

Bacterial and eukaryotic nitric oxide synthases (NOS), which produce NO by catalyzing the oxidation of L-arginine to L-citrulline, are structurally and mechanistically related (*1*, *2*). Although bacterial NOS (bNOS) lacks the essential reductase domain, it uses available cellular reductases to generate NO in vivo (*3*). Previously, we demonstrated