# The Real Cost of Wind Energy

The cost of electricity from wind is about 4 ¢ per kilowatt-hour (kWh) according to M. Z. Jacobson and G. M. Masters' estimate in their Policy Forum "Exploiting wind versus coal" (*Science*'s Compass, 24 Aug., p. 1438), making wind energy competitive with new coal-fired generation. There is a 1.5-¢/kWh federal credit for wind energy producers, and, in addition, consumers are willing to pay a premium for wind. Given this credit, and a conservative 0.5-¢/kWh green power premium (1), one might expect wind producers to break even at ~6 ¢/kWh. If their costs are 4 ¢/kWh, producers should make large profits and wind should dominate new electric capacity. No such boom is observed; wind generates only 0.1% of U.S. electricity and accounts for only 1% of capacity additions in the last 5 years (2). Two factors--transmission and intermittency--raise the real cost of wind and explain the discrepancy between simple estimates of cost and observed installation of capacity.

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Jacobson and Masters propose replacing ~60% of coal capacity with wind farms in North Dakota that have an average power of ~130 GW. At this scale, wind is a significant fraction of capacity, and its intermittency must be addressed. To derive a conservative estimate for the cost of backup generation under suboptimal wind conditions, suppose that 130 GW of gas turbine capacity is installed. Wind power generated beyond the mean output can be sold, roughly compensating for fuel costs when backup generation is used. The amortized cost of the gas capacity is ~1 ¢/kWh. In addition, Jacobson and Masters dismiss transmission costs, suggesting that they "can be offset with turbine mass production." We are unconvinced. The best sites for wind farms are in the Great Plains, far from demand centers concentrated on the coasts, so transmission costs must be included if wind is to supply a significant fraction of national demand. Using modern HVDC (high-voltage direct current) technology, transmission costs are ~1.5 ¢/kWh for 2000-km lines (3). Therefore, combining the cost of backup and transmission adds 2 to 3 ¢/kWh to the cost of wind, partially explaining the discrepancy between simple cost estimates and observed behavior.

We believe that the challenges posed by remoteness and intermittency are surmountable, but it is an exaggeration to say that wind is now competitive with coal.

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### References and Notes


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2. Energy Information Administration, "Annual energy review" (modified Oct. 2001) (http://www.eia.doe.gov/emeu/aer/contents.html)
3. Calculation based on *HVDC Power Transmission Technology Assessment Report ORNL/Sub/95-SR893/1* (Oak Ridge National Laboratory, Oak Ridge, TN, April 1997).


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### Response

We disagree with Decarolis and Keith's key points and believe that our conclusions still stand. First, DeCarolis and Keith speculate about the intermittency cost of wind (the cost of regulation ancillary service), but there is no need to speculate, because a study on this issue has been done. It showed that such costs are about 0.005 to 0.03 ¢/kWh, which is less than 1% of the price of wind energy, and the cost can be reduced further by using an hour-by-hour persistence forecast (1). In addition, the more turbines at a given wind farm and the more wind farms there are, the more intermittency of individual turbines cancel each other out (for example, lower supply from one farm can be made up by greater supply from another) (2).

As for the issue of transmission of wind-generated electricity, the National Renewable Energy Laboratory estimates that 175,000 MW of potential wind power are within 5 miles (8 km) of existing 230-kV or lower transmission lines, 284,000 MW within 10 miles (16 km), and 401,000 MW within 20 miles (32 km) (3). Sites close to transmission lines would be developed first. If North Dakota or other remote locations are fully developed, the cost of above-ground AC transmission lines range from $120,000 to $840,000 per mile (~$75,000 to $520,000 per km) (4). Assuming an average cost of $310,000 per km ($500,000 per mile), the cost of 10,000 km of new lines is $3.1 billion, less than 1% of the cost of 225,000 new turbines. Over distances greater than 500 km, HVDC lines are less expensive and lose less energy than AC lines (5). The transmission cost of 1.5 ¢/kWh that DeCarolis and Keith mention is not supported by the actual cost of transmission lines, nor would it be applicable over the many decades that transmission lines would be used.

The authors also use wind cost statistics from past experience, which are not applicable to current turbine technology. Turbines in the past have had relatively high ratios of rated power ($P$) to diameter squared ($D^2$). The turbine used in our example ($P$ = 1500 kW, $D$ = 77 m) has a low ratio, giving it a greater capacity factor than a turbine of the same power but lower diameter (6). Plus, newer turbines are taller than older turbines, and wind speeds increase with increasing height. As such, one cannot use old statistics to argue against new technology.

Contrary to the authors' statement that no wind boom has been observed, wind energy today has the fastest growth rate of any new source of electricity in the world. Because the base amount of wind energy is so small, it will take awhile, even at fast growth rates, for wind to gain a large market share. DeCarolis and Keith also mention wind subsidies, but what about current and historic coal and natural gas subsidies, including exploration and mining tax credits, preferential loan interest rates for fossil-fuel power plants, long-term utility contract subsidies to coal, gas pipeline subsidies, and greater federal funding of coal- and natural gas-technology programs, not to mention portions of the cost of the U.S. Acid Deposition Program and U.S.

Environmental Protection Agency for cleanup and monitoring of pollution attributable to these industries· In addition, we should not ignore the costs from coal and natural gas's exacerbation of acid deposition, urban smog, human health and mortality, visibility degradation, and global warming.

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## References and Notes

1. E. Hirst, *Interactions of Wind Farms with Bulk-Power Operations and Markets* (September 2001) (http://www.EHirst.com/PDF/WindIntegration.pdf).
2. Danish Windturbine Manufacters Association, "21 Frequently Asked Questions About Wind Energy" (updated 16 April 2001) (http://www.windpower.dk/faqs.htm).
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4. J. Makens, *Upgrading Transmission Capacity for Wholesale Electric Power Trade* [modified 17 May 2001], table FE2 (http://www.eia.doe.gov/cneaf/pubs_html/feat_trans_capacity/table2.html).
5. Greenhouse Gas Technology Information Exchange (GREENTIE), "High Voltage Direct-Current Transmission" (modified March 2001) (http://www.greentie.org/class/ixd04.htm).
6. The capacity factor equation has been verified independently to within 2.8 to 3.5% of our calculation by Enron Wind, a wind power company. They determined the annual energy yield of their 1500-kW, 77-m turbine (the one used in our example) as a function of mean Rayleigh wind speed {Enron Wind, "1.5 [wind turbine] Technical Data," figure 2 (cited September 2001) (http://www.wind.enron.com/PRODUCTS/15/15data.html)}. The comparative numbers in units of kWh/year (divide these numbers by 8760$P$ to obtain the capacity factor) are as follows:

| Mean Rayleigh wind speed | 7 m/s | 7.5 m/s |
|---|---|---|
| Our calculation $E = 8760P(0.087VP/D^2)$ | $4.68 \times 10^6$ | $5.26 \times 10^6$ |
| Enron's data | $4.55 \times 10^6$ | $5.08 \times 10^6$ |

[$V$ is the mean annual Rayleigh-distribution wind speed (m/second), $P$ is the rated power (kW) of the turbine, and $D$ is the diameter of the turbine (m).]

quence-tag databases or whole-genome sequence information. The development of these tools will be essential for helminthology questions to compete successfully in the real world of grant requests and study sections.

The situation resembles the abyss in which public health officials found themselves when Multi-Drug Resistant (MDR) tuberculosis arose in the late 1980s; there were few researchers or trained students interested in staying in the field, and no drug alternatives. The immediacy and threat of MDR TB rapidly induced funding of high-risk, technology-driven grants over a period of 4 to 8 years, which resulted in mycobacteria study becoming a vibrant, active field.

For a number of years, several philanthropic foundations have recognized the global importance and neglected nature of helminthic infections. Their efforts have been critical but not sufficient to sustain the level or focus of effort needed. We propose an "Affirmative Action for Worms" program that could attract senior and junior scientists from other fields, foster those few languishing investigators who know these systems, and entice researchers into the high-risk areas of worm-related technology development and applied usage. A 5-year, highly competitive program of \$40 to \$50 million, that fostered and integrated bench and field research with multiple-level training programs could lead to a real reversal in the current downward spiral of research.

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POLICY FORUM: ENERGY

# Exploiting Wind Versus Coal

**Mark Z. Jacobson* and Gilbert M. Masters**

Much of the recent energy debate in the United States has focused on increasing coal use. However, the cost of wind energy is now less than that of coal. Shifting from coal to wind would address health, environmental, and energy problems.

Energy costs from a new coal power plant are low [(3.5 to 4 ¢/kWh) (*1*)], but coal-mine dust kills 2000 U.S. miners yearly, and since 1973, the federal black lung–disease benefits program has cost \$35 billion (*2*). Coal emissions also cause acid deposition, smog, visibility degradation, and global warming; its particles increase asthma, respiratory and cardiovascular disease, and mortality (*3*). Health and environmental costs bring the total costs to 5.5 to 8.3 ¢/kWh (*4*).

Wind is a clean energy source. We estimate its costs as follows: installing a 1500-kW turbine with a 77-m rotor diameter and design life of 20 years costs \$1.5 million (*4*–*7*), which pays for the turbine (80%), grid connection (9%), foundation (4%), land (2%), electrical installation (2%), financing (1%), roads (1%), and consultancy (1%) (*4*, *7*). Amortizing this over 20 years at 6 to 8% interest gives \$131,000 to \$153,000 per year. Adding annual operation and maintenance (O&M) (*4*, *6*, *7*) leads to an estimated annual cost of \$149,000 to \$183,000.

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A turbine's annual energy output (kilowatt-hours/year) is about $P \times 8760 \times (0.087V\text{-}P/D^2)$ (*7*), where $P$ is rated power (in kilowatts), $V$ is mean annual wind speed (meters/second) at rotor height ~50 m, $D$ is rotor diameter (meters), and 8760 is hours/year. With a mean annual 50-m wind speed of 7 to 7.5 m/s [which occurs across all of North Dakota, 70% of South Dakota, and large tracts of the West, Great Plains, East, and Northeast (*8*)], the turbine energy produced is 4.7 to 5.2 × $10^6$ kWh/year. Dividing turbine cost by energy produced and adding manufacture and scrapping costs (*7*) gives the energy cost of a large turbine as 3 to 4 ¢/kWh. Reported costs for large plus small Danish turbines are 4 ¢/kWh (*9*). These numbers suggest that the total costs of wind energy are less than those of coal energy.

Under the 1997 Kyoto Protocol, the United States proposed to reduce greenhouse gas emissions to 7% below 1990 levels. As of 1999, the target could be satisfied by replacing 59% of 1.89 × $10^{12}$ kWh/year (*10*) in coal energy with 214,000 to 236,000 turbines, thereby reducing coal-$CO_2$ emissions (499 Tg-C/year) (*11*) by 59%. At six turbines per square kilometer, the turbines could be spread over 194 × 194 $km^2$ of farmland or ocean.

Alternatively, every 36,000 to 40,000 turbines could displace 10% of U.S. coal at a cost of \$61 to \$80 billion, including O&M plus initial costs (also the present value of payments to date from the black lung–disease benefits program). This could be supported at no net federal cost by investing 3 to 4% of one year's \$2.02 trillion budget in turbines and selling the electricity over 20 years. Similarly, California could provide 10% of its 1999 electricity (2.35 × $10^{11}$ kWh/year) (*12*) by buying 4500 to 5000 turbines at 7.5 to 9.9% of one year's \$101 billion budget and selling the electricity over 20 years.

One concern with turbines is harm to birds This might be mitgated by siting turbines out of migration paths. Also, turbine output is unresponsive to electricity demand. This is moot when wind is one of many energy sources. Finally, remote turbines require extra transmission lines. This cost can be offset with turbine mass production. Government promotion would also catalyze private investment.

By 2000, Germany had 6113 MW of installed turbines, more than the United States (2554 MW) or Denmark (2300 MW) (*13*). Sweden and Denmark have wind parks offshore, where winds are faster than over land. Clearly, the United States has not maximized its wind potential.

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14. Funding was provided by the EPA, NSF, and NASA.

# dEbate responses to:

letters

**The Real Cost of Wind Energy**

Joseph F. DeCarolis, David W. Keith, Mark Z. Jacobson, and Gilbert M. Masters

*Science* 2001; 294: 1000-1003 [Full text]

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- **Response to letter by Howard Gruenspecht of November 21, 2001**
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## Don't Dismiss the Midwest's Power Needs

2 November 2001

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Re: Don't Dismiss the Midwest's Power Needs

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In their argument against wind power, DeCarolis and Keith dismiss this method of power generation in part because the best generation would come from the Great Plains, "far from demand centers concentrated on the coasts." Even if transmission costs prohibited transcontinental power distribution, Denver, Chicago, Minneapolis, Milwaukee, St. Louis, Indianapolis, Detroit, Des Moines, Topeka, Kansas City, Winnipeg, Calgary, Saskatoon, Edmonton, and, possibly, Dallas and Houston would benefit greatly from plains-derived wind power. Even if it cost the same or slightly more, wind power would allow more polluting resources to be made available to the coasts. Just because a good energy solution might not benefit America's coastal cities does not mean it should be ignored.

## Wind vs. Coal

14 November 2001

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Jacobson and Masters (24 Aug., p. 1438) make the case that wind-derived electricity could replace a significant fraction of coal derived electricity, thereby reducing coal carbon dioxide emissions by up to 59%. The cost of wind-derived electricity is comparable with that of coal-derived electricity. There is no doubt that a wind turbine does not emit any carbon dioxide (except that emitted by fossil fuels used to fabricate and construct the turbine), and does not emit any of the other harmful air pollutants associated with mining, transport, and combustion of coal. But in balancing the cost-benefit equation, we should be more judicious. Because wind is intermittent, back-up power generators must be available. Even in North Dakota, arguably the windiest state in the United States, winds do not blow all the time. For example, in Bismarck, North Dakota, winds are calm 5% of the time, and blow less than 3 m/s 40% of the time (1). (The efficiency of wind turbines declines precipitously when winds blow less than 3 m/s.) Thus, wind power cannot replace conventional power generators, but only displace the fuel that conventional generators would use when the wind generators are in operation. Many coal fired power plants supply the base load, because they cannot follow the fluctuating demand during peak hours. Peak power is mainly supplied by gas or diesel fired generators. An efficient combined cycle gas fired power plant might emit only half as much carbon dioxide per kilowatt hour as a coal fired generator, so the savings in carbon dioxide emissions by wind generators might be much less than Jacobson and Masters calculated. Typically, the fraction of fuel cost to total production cost of pulverized coal fired electricity generators is in the 24 to 30% range, and of natural gas combined cycle generators is in the 48 to 58%

range (2). Thus, it is not correct to compare the total cost of coal versus wind generating costs, and total carbon dioxide emissions of coal versus wind, but only the fuel cost and carbon dioxide emissions that wind power displaces when the wind generators operate.

This is not to say that wind-derived electricity is not worthwhile. The savings in carbon dioxide and other pollutant emissions are real, as well as the savings in fuel cost. But the cost-benefit equation must be properly balanced.

References and Notes

1. Data supplied by J. Enz, State Climatologist, North Dakota State University.

2. Same as reference 1. in M. Z. Jacobson and G. M. Masters, Science 293, 1438 (2001).

## Re: Wind vs. Coal

14 November 2001

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We disagree with Golomb's premise and believe that our conclusions still stand. If wind energy replaces 59% of coal energy, then wind will supply about 30% of U.S. electricity, whereas 70% of electricity will still be supplied by other sources. As such, there is still plenty of backup electricity even if wind energy for a day hypothetically went to zero, which is not even a remote possibility, given the consistency of daily U.S.-averaged winds. The issue then is, what is the intermittency cost (the cost of regulation ancillary service) of wind. A study on this issue has been performed, and it shows that such costs are about 0.005 to 0.03 cents per kilowatt hour (kWh), which is less than 1% of the price of wind energy (1). The cost can be reduced further simply by using an hour-by-hour persistence forecast at the given location (1). In addition, the greater the number of turbines at a given wind farm and the greater the number of wind farms, the more intermittency of individual turbines cancel each other out. One can imagine a scenario where winds are slow one day at one wind farm. These slow wind speeds can be made up for by power generated at one of several other farms, where wind speeds are faster. It should also be noted that winds near the coast and offshore are regular and predictable and subject to less intermittency than winds away from the coast. Based on the above, we believe it is incorrect to state that wind cannot replace conventional power generators. Further, our paper discussed replacement of coal with wind, but we also believe that new wind should replace new natural gas, whose emissions enhance acid deposition, urban smog, human health and mortality, visibility degradation, and global warming, all of which have real costs. In sum, we believe our conclusions stand.

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2. Danish Windturbine Manufacters Assoc. (2001). http://www.windpower.dk/faqs.htm

## Re: Re: Wind vs. Coal

21 November 2001

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I would agree with the letter writers that it is an exaggeration to say that wind is competitive with coal. I have examined the issues of distance from demand centers and intermittency. My most recent paper was published in the November issue of JSEE in which I compared storage costs.

Intermittent wind generated electricity can be transformed to a constantly available power supply economically by using compressed air energy storage (CAES) systems. Costs, including transmission and storage costs, are computed for a realistic system in (1).

Transmission lines are not only costly, but quite difficult to site. Nobody wants one in their neighborhood. This can be overcome, but it takes great diplomacy and political will to accomplish.

I do believe that wind energy could supply all of the electricity needed by the United States at a reasonable price, but it will cost more than market priced coal, which does not take into account any environmental damage from coal mining, acid rain, or global warming. People should be prepared to pay a premium for wind energy, or they should be prepared to penalize dirty power to reflect its real cost.

There is indeed a boom in wind energy in Europe, but it is not caused by cheap (relative to natural gas or even imported coal) wind power. Wind power receives premium payments to reflect its attributes. This same approach should be used in the United States, and indeed the U.S. Production Tax Credit program does just this. The program is passed for only a few years at a time, then allowed to lapse, guaranteeing turmoil in the U.S. industry.

Europe has made a policy decision to support clean power at a reasonable cost, even if it is more costly than fossil fuel generated electricity. The United States should do the same.

References and Notes

1. High Capacity Factor Wind Energy Systems, JSEE 117, 137 (May 1995).

## Response to Jacobson and Masters

21 November 2001

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We have enjoyed our dialog about the cost of large-scale wind energy. We judge that much - perhaps all - of our disagreement stems from differing assumptions, rather than dispute over the factual content such as the cost and performance of wind turbines or the cost of long-distance transmission. With this letter, we aim to make our assumptions explicit and then respond to Jacobson and Masters' critique of our letter to Science.

We assume the following: 1. Wind energy could realistically effect deep reductions in the environmental damages (air pollution, $CO_2$) imposed by fossil-based electric power systems. 2. In response to the $CO_2$-climate problem, we expect that it will be necessary to make deep reductions (over 50%) in electric sector emissions. We are interested in estimating the cost of wind if it were to supply a substantial fraction, on the order of one-fourth, of U.S. demand. 3. If wind is to be exploited at very large scales (hundreds of gigawatts of output), we anticipate that environmental, aesthetic, and economic considerations will dictate that the bulk of the wind capacity be located in the windy regions of the Great Plains.

Below we address the critiques you raised regarding our letter.

1. Hirst's analysis and intermittency. We were impressed by Hirst's analysis, "Interactions of Wind Farms With Bulk-Power Operations and Markets,"(1). The paper analyzes import of wind energy from the Lake Benton site in southwestern Minnesota to the PJM grid. The analysis is, however, not pertinent to our disagreement about the cost of intermittency because it treats a case where the wind power supply is too small to significantly influence the power market. The Benton array has a small capacity (~100 megawatts) and is being imported into a massive grid capable of supporting a peak load of 52 gigawatts. Hirst addresses this issue by adding a wind multiplier parameter, but his analysis still only extends to wind serving less than 10 percent of generation. Hirst's general conclusion only supports our intuition: "as the size of the wind farm increases relative to the control area, the average price it receives for its output declines."

2. The economics of backup when wind is baseload. There is an additional complication not presented in the Hirst paper that is only relevant when wind is treated as baseload capacity. Although geographically dispersing turbine arrays can decrease the variance in wind power output, there will still be times when turbine output is minimal. Therefore, there must be a significant amount of backup capacity or storage. But because many of these generating or storage units will be used infrequently only when the wind doesn't blow, there use will be small and the amortized cost will be spread over fewer kilowatt hours of production, making the incremental cost of backup very expensive. Given points 1 and 2, we think your suggestion that

the cost of intermittency is of order 0.05¢/kWh is implausible. We think our disagreement here is completely driven by differing assumptions about wind's fraction of electric capacity.

3. Correspondence between wind resources and the existing grid. We do not dispute your statement that several hundred gigawatts of wind resources exist within 10 miles of existing transmission infrastructure (2). However, we think that this may not be relevant for three reasons detailed below.

(a). Economic considerations. Exploiting wind resources close to existing transmission grids is not necessarily the most cost-effective solution. Because wind turbine output exhibits a cubic dependence on wind speed, wind power output is very sensitive to location. For instance, it may be true that installing 10 gigawatts of turbine capacity in the Pembina Escarpment of North Dakota, a wind class 5 area, and transporting the electricity to the PJM grid via HVDC lines is roughly equivalent in cost to simply installing the wind turbines in southwestern Pennsylvania, in wind classes 3-4 and neglecting transmission costs. For the same reason, we do not believe it is coincidental that Hirst chose to look at wheeling wind power from Lake Benton, a wind class 6 site, to the PJM grid.

(b). Transmission considerations. In addition to considering the location of wind turbines with respect to the existing grid, a comprehensive assessment of existing transmission and distribution line capacity of the local grid must be performed, as your reference clearly indicates (2). We would wager that the existing grid located near the Pembina Escarpment would not support the hypothesized 10 gigawatts of additional electric power from new turbine arrays. As such, we still believe that long-distance HVDC transmission lines would be a critical component of large-scale wind. Jacobson and Masters say that the cost of 1.5 ¢/kWh "is not supported by the actual cost of transmission lines," but they provide no reference to other estimates of HVDC costs. We can cite many studies that show amortized HVDC costs to lie in the 1-2 ¢/kWh for these distances.

(c). Aesthetic considerations. Although there are substantial wind resources near population centers (and the grid), we are skeptical that these would be developed at large scales. For example, where we live in western Pennsylvania, there are substantial wind resources located on the mountain ridges, and in principle these could supply power to the PJM grid. However, to supply substantial power a developer would need to use almost all the ridge tops, which we believe would be unacceptable to local residents. We judge that aesthetic and environmental concerns would push large-scale wind into the Great Plains.

4. Wind versus coal. We realize that electricity production from coal results in significant environmental externalities, which must be addressed. Rather than speculating on the costs of coal externalities, we assume that coal with carbon capture may present a comparable solution to wind by minimizing power plant emissions. Such costs will likely raise the price of coal to the 5-7 ¢/kWh range (3, 4). This is the price wind will need to compete against. As for the cost of wind, we simply used your claim of 3-4 ¢/kWh for the amortized capital cost of wind turbines, and are therefore confused by your statement that “the authors use wind cost statistics from past experience.” We do not seriously dispute your estimate of the average cost of wind generation at a given site.

We believe that wind may present an economically viable alternative to coal with carbon capture, but to assert that, “the cost of wind energy is now less that of coal” is not accurate. If it were, we would expect to see wind dominate virtually all new capacity installations (given the 1.5 ¢/kWh tax incentive), rather than simply having the fastest relative growth rate – not an overly impressive statistic for an energy technology that is cheaper than coal.

We welcome any feedback and would like to continue this dialog.

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1. E. Hirst, Interactions of wind farms with bulk-power operations and markets, http://www.EHirst.com/PDF/WindIntegration.pdf, 2001.

2. M. Shaheen, Wind Energy Issue Brief 9a (October 1997) (http://www.nationalwind.org/pubs/wes/ibrief09a.htm).

3. E.A. Parson and D.W. Keith Science 1998 November 6; 282: 1053-1054.

4. H. Herzog, The Economics of CO2 Separation and Capture, Technology, 7, pp. 13-23 (2000).

## Re: Re: Wind vs. Coal

21 November 2001

Howard Gruenspecht,
Resident Scholar
*Resources for the Future*

Letters from DeCarolis and Keith (Science, Nov. 2) and Golomb (dEbates, Nov 14) argue that the cost of contingency reserves to back up intermittent wind power omitted from the Jacobson and Masters proposal(Science, Aug. 24, p. 1438) to substitute wind for coal on a massive scale is significant. In response, Jacobson and Masters (Nov.

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2, Nov 14) reference a recent paper by Hirst (1), which they say shows that these costs are trivial. However, the cited paper explicitly states that its ancillary service cost estimates for integrating wind do not include contingency reserves. Hirst's rationale for excluding contingency reserves, that wind farms (typically a fraction of 1 gigawatt (GW) capacity) do not contribute to the need for reserves required to meet the largest system contingency (typically in the range of 1 GW), clearly does not apply to the Jacobson and Masters proposal to install 321 to 354 GW of wind in the Dakotas.

Where wind variation is the largest system contingency, as it would be under the Jacobson and Masters proposal, conventional reliability criteria would require reserves sufficient to meet load under the calmest 1-day-in-10-year wind conditions. With the rapid drop in generation as wind speed falls below its mean level (according to references cited by Jacobson and Masters, generation drops to zero at roughly 3 m/s), required contingency reserves equal to a significant fraction of the wind capacity envisioned under the Jacobson and Masters proposal would be needed. Significantly, Golomb notes that average windspeed in Bismarck is less than 3 m/s 40 percent of the time - a sobering consideration, given the likelihood of significant correlation in wind conditions across individual windfarm sites in North Dakota.

DeCarolis and Keith also say that there are likely to be significant costs of moving power to load centers. In response, Jacobson and Masters outline a calculation that costs 10,000 km of transmission lines at $3.1 billion, less than 1% of wind turbine costs. However, 10,000 km provides only 30 km of transmission per gigawatt of wind capacity added under their proposal. This could perhaps meet local interconnection and grid enhancement needs, but not the need for long-distance transmission to load centers. Existing project proposals provide a firmer basis for estimating the latter cost. For example, Siemens and Black, and Veatch, experienced power system engineers and vendors, have recently analyzed a plan to add 8 GW of capacity in North Dakota and connect it to load centers in the Chicago and Los Angeles area by HVDC transmission.(2) Subtracting generating capacity costs from their $15 billion total project cost estimate suggests a transmission component cost of roughly $5 billion. A system capable of carrying 8 GW from North Dakota to only one load center would probably cost $3 billion, since two of the three sets of AC/DC converters would still be needed. Eight gigawatts is only 2 to 2.5 percent of the power that would be moved under the Jacobsen and Masters proposal, validating the DeCarolis argument that long-distance transmission costs are more than noise in the overall cost evaluation of that proposal.

In addition to the foregoing comments related to previous exchanges, Jacobson and Masters' focus in theiroriginal Policy Forum on comparisons between the levelized costs of new wind and coal plants is something of a red herring because their actual proposal involves replacing generation from existing coal-fired plants, which costs 1 to 1.5 cents per kilowatt-hour, with new wind power. Furthermore, in cases where new capacity is needed now, the overwhelming choice in today's markets is for gas-fired units, which are both cheaper and cleaner than coal, but not even mentioned. Information they provide regarding black-lung deaths is also misleading in the context of this article. Most black-lung cases reflect past, not current, mining practices, and the number of black-lung deaths would not be appreciably impacted by the prospective reduction in coal use under their proposal.

Competition between coal-fired and wind-powered generation will likely grow increasingly important over time. Each will have to overcome fuel-specific hurdles. For wind, these include the costs of contingency reserves and the need to overcome public objections to siting new transmission lines and turbines. For coal, these include the costs of increasingly stringent controls on conventional pollutants and the likely future requirement to capture and sequester carbon emissions. Notwithstanding the shortcomings of the Jacobson and Masters analysis, wind appears well-positioned to provide an important share of generation capacity additions over the coming decades.

References and Notes

(1) Hirst. Same reference #1 in Jacobson and Masters, Nov 2

(2) Engineering News Record, June 11, 2001 @ http://www.bv.com/bv/news/articles/grid_sols.htm

## **Response to Alfred Cavallo letter of November 21, 2001** 28 November 2001

Mark Z. Jacobson and Gilbert M. Masters, Associate Professor (MZJ); Professor (GMM)
*Department of Civil and Environmental Engineering, Stanford University*

We thank Cavallo for his contribution to this debate. However, we believe his letter misstates the comparison made in our paper. Second, his implication that wind power is not cheap relative to natural gas or coal is contradicted by a third-party analysis of 17 California wind proposals in 2001 that supports our conclusion that the direct cost of wind is 3 to 4 cents/kWh. Third, his implication that the Production Tax Credit reflects the attributes of wind is contradicted by the stated purpose of the credit. Finally, we believe his comments about transmission lines are misplaced and his cost estimates of transmission lines too high.

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First, Cavallo implicitly assumes that we compared the direct cost of new wind with the direct cost of all (old + new) coal. Instead, our paper compared (i) the direct cost of new coal with that of new wind, and (ii) the direct + health/environmental costs of new or old coal with those of new wind (since the health/environmental costs of old coal are higher than those of new coal, the total cost is likely to be similar in both cases). Nowhere did we discuss the direct cost of old coal with that of new wind, nor do we believe this matters from a public policy point of view. From such a point of view, the only relevant issue is the total (direct+health/environmental+subsidy) cost of wind versus that of coal because whether wind replaces coal is a political, not a marketplace, decision (regrettably, we did not discuss coal or wind subsidies in our original paper). It is not a marketplace decision because, even when wind and old coal prices are exactly the same, there is no incentive for coal producers merely to fold up. Coal producers will fold up only when government decides to (i) require old and new coal to eliminate emissions, (ii) require old and new coal to pay for the health and environmental damage caused by remaining emissions and mining, and (iii) reduce the subsidies given to coal in excess of those given to wind. At the same time, government itself can promote wind to ensure that new fossil energy does not take a larger foothold.

Second, we believe our estimated direct cost of energy from wind (3 to 4 cents/kWh) is correct for the conditions assumed and is beginning to be reflected in wind proposals. For example, Bolinger and Wiser (1, p. 3) calculated the 25-year real costs of 17 wind farm proposals in California in 2001 as 3.2 to 3.7 cents/kWh, with a weighted average value of 3.6 cents/kWh. Their analysis also stated that the numbers were based on proposal information that presumably contained worst-case estimates for wind.

Third, Cavallo says that "wind power receives premium payments to reflect its attributes...and indeed the U.S. Production Tax Credit program does just this." This is incorrect. The purpose of the tax credit is to level the playing field in terms of past and current subsidies that have favored the development of coal and natural gas technologies and that have kept the price of coal and gas low. Specifically, the House Ways and Means Committee stated (H. Rpt. 102-474, Part 6, p. 42),

"The Credit is intended to enhance the development of technology to utilize the specified renewable energy sources and to promote competition between renewable energy sources and conventional energy sources."

The credit does not address the attribute of renewable energy, namely, its health, environmental, and climate benefits over natural gas and coal. It addresses inequities in past and present subsidies. Even with the tax credit, tax and current direct government subsidies to coal and natural gas far exceed those of wind. Current tax and other subsidies for coal and natural gas are in the billions of dollars per year (http://www.foe.org/DLS for starters), whereas subsidies under the Production Tax Credit are on the order of $100 million per year.

Fourth, we believe Cavallo's comments about transmission lines are out of context. He states that "transmission lines are not only costly, but quite difficult to site." We agree with these general statements but do not believe that translates into a high cost per kilowatt hour for wind energy.

(i) Transmission access pathways already crisscross the United States, and many already pass through the Great Plains. If new, long transmission lines are needed for wind plants, most of these lines can piggyback on existing transmission towers, and smaller transmission lines on existing towers can be upgraded. Adding new lines to existing towers or replacing existing lines is less expensive than creating new towers. Only local connections to the nearest long-distance transmission pathway require siting of new transmission pathways.

(ii) Whether the high cost of transmission lines per unit distance translates into a high cost per unit energy (kWh) depends on the length of the transmission line, so it is incorrect to label transmission costs as "high" without specifying the length of the line.

Cavallo (2) estimated the cost of transmitted energy through a 2000-km HVDC transmission line as 2.75 cents/kWh. This translates to 0.00138 cents/kWh/km. Cavallo assumed a capital charge rate of 0.107, which translates to an interest rate of nearly 9% over 20 years. However, transmission lines can last 40 to 60 years. Further, commercial interest rates today are lower than 9%. These combined factors alone would reduce Cavallo's estimate by a factor of 2. Cavallo also acknowledged that the transmission line cost used was conservative and "could be about one-half what we have assumed" (2). Changes in assumptions about interest rate, transmission line lifetime, and direct costs would change Cavallo's transmission cost estimate to 0.000345 cents/kWh/km. This estimate could be reduced further by piggybacking new lines on existing transmission powers. Nevertheless, the 0.000345 cents/kWh/km cost is 1% of our estimated direct cost of wind energy (3 to 4 cents/kWh) when the average transmission line is 88 to 116 km long. Even if the average transmission line is 500 km long, the cost is still less than 5% of the direct cost of wind (and <1.5% the price a typical consumer pays for electricity, which is 11 cents/kWh). In the worst case (2000 km line), the cost is around 20% of the direct cost of wind (and <6% the price a consumer today pays for electricity).

We have cited before that 840,000 MW of wind power lie within 20 km of existing transmission lines. Our proposal requires the generation of only 128,000 MW of power (225,000 1.5-MW turbines in the presence of 7 to 7.5 m/s winds, giving capacity factors of 0.35 to 0.4). Clearly, a reasonable portion of our required power can be obtained from turbines close to existing transmission lines. If such lines are already saturated with power, the cost of additional lines is not a cost of wind exclusively but a shared cost among all energy sources using the lines, because coal and natural gas generally do not own such lines, and therefore, do not have an exclusive right to them.

In sum, we suggest that higher cost of long transmission lines is compensated for by lower cost of shorter transmission lines. If the average transmission line is less than 100 to 500 km long, the resulting cost of energy related to transmission lines is less than 1 to 5% of the price of wind energy.

(c) In his letter, Cavallo says that transmission costs are high for wind but omits the fact that, when comparing coal and wind, it is necessary to compare the transmission costs of both, not merely to state that wind has a high transmission cost. There are thousands of coal plants in the United States and tens of thousands of miles of transmission lines needed to transmit coal energy. Not only do current transmission costs exist for coal, but when coal transmission lines do wear out (and most are fairly old now), they need replacing.

References and Notes

1. M. Bolinger, R. Wiser, Summary of Power Authority Letters of Intent for Renewable Energy, Memorandum, Lawrence Berkeley National Laboratory, 30 October 2001.

2. A. J. Cavallo, High-capacity factor wind energy systems, JSEE 117, 137 (1995).

## Response to DeCarolis and Keith response of November 21, 2001

28 November 2001

Mark Z. Jacobson and Gilbert M. Masters, Associate Professor (MZJ); Professor (GMM)
*Department of Civil and Environmental Engineering, Stanford University*

We thank DeCarolis and Keith for their important comments and for furthering this debate. We believe that we have reached convergence on several issues and that some issues will not be completely resolved at this time. On other issues, though, we still respectfully disagree, and we believe that the conclusions of our original paper still hold. Below are responses to DeCarolis and Keith's points in their response of 21 November 2001, in the order they are given.

(Point 1) Hirst's (2001) analysis addressed one aspect of intermittency, the cost of regulation ancillary service. He found the cost

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to be small (0.005 to 0.03 cents/kWh, less than 1% of the direct cost of wind energy). A similar study was performed by Hudson et al. (2001) who also found that the cost of regulation ancillary service to be small when wind is integrated into a grid (0.006 cents/kWh).

(Point 2) As DeCarolis and Keith correctly point out, there is a second issue related to intermittency, and this is the potential cost of supplying backup energy when wind becomes a large fraction (e.g., 30%) of energy supply and wind's output is low for a given hour. The real question here, though, is not what is the cost to wind, if any, in this case, but what is the difference between the cost to wind and the cost to coal or natural gas (since we did not account for this potential cost with respect to either coal, natural gas, or wind in our paper).

We suggest that the cost to wind due to backup reserves could be less than or more than that to natural gas and coal and the net cost, either way, is uncertain. As such, we believe it is incorrect to presume a cost or a benefit as DeCarolis and Keith have done. Before the work of Hirst and Hudson et al., it was commonly presumed that wind had a high cost of regulation ancillary service. This assumption turned out to be incorrect. Similarly, it should not be presumed that expansion of wind energy will result in a higher cost of contingency reserves than the current cost. The main reasons we believe the net difference in contingency reserve costs could be either negative or positive are given as follows.

First, backup sources of power are already in place and are used when natural gas or coal power plants fail, supplies tighten, or energy demand increases beyond expectations suddenly. The forced outage rate for all fossil fuel power plants is, on average, 8% (North American Electric Reliability Council, 2000). This compares with a failure rate for modern wind turbines of 2% (Danish Windpower Manufacturers Association, 2001). As such, if wind displaces coal, the reliability rate of replaced energy, in terms of energy source failure alone, will improve immediately by 6%. DeCarolis and Keith use in their example a peak load of 52 GW. If 30% of 52 GW is supplied by replacing coal with wind, backup requirements for failure will be reduced by 1 GW. Replacing natural gas with wind will result in a proportional reduction.

Second, whereas wind is an intermittent energy source, natural gas is also an intermittent energy source. This is evidenced by the variations in natural gas prices of 50 to 100% from month to month and year to year (e.g., McFeat, 2001). This price variation is caused in large part by a variation in natural gas supply. The variability of natural gas supplies and prices suggests that, if wind replaces natural gas, backup requirements may not change much.

Third, peaker plants are used commonly today when energy demand exceeds expectations. Thus, a certain amount of backup is already necessary, regardless of the energy source.

Fourth, there are several ways to provide backup energy. Some include increasing hydroelectric output, transmitting from outside the grid, using peaker plants (usually fossil fuel), and storage.

(i) Hydroelectric power supplies 10% of energy in the United States (only 4% outside of California, Oregon, and Washington). When hydroelectric output is increased as a backup, there is little additional cost.

(ii) If wind becomes 30% of the energy supply, wind farms will be distributed over greater areas, and grid interconnections will expand, enabling easier transmission of excess wind, solar, hydroelectric, and fossil energy from outside the local grid, thereby reducing and potentially eliminating the need for peaker plants for backup. In other words, the expansion of wind energy may reduce the cost of backup energy by enlarging the size of a grid and by facilitating transmission of excess wind and other types of energy from outside the grid when needed.

(iii) A large future energy requirement may be to generate hydrogen for fuel cells. In such a case, intermittency is no longer an issue, and only total energy output over a year is. Wind is reliable for producing an aggregate amount of energy over a period of a month to a year.

(Point 3)(i) Whereas we agree that the Great Plains contains the largest concentration of ideal wind sites, there are plenty of land and water sites with equal or greater wind power that have still not been exploited. The fastest wind sites in the country (>9.4 m/s on average) are all along the coast, such as of North Carolina, South Carolina, and and Louisiana (Archer and Jacobson, 2001, first figure - please note that the figure gives speeds at the measurement locations only). Sites exist in numerous states that are very fast.

(ii) For a distance of 2000 km, we estimate the cost of new HVDC lines as about 0.7 cents/kWh (see footnote), which is about half the average value given by DeCarolis and Keith (although the uncertainty is within the margin of error of their estimate). However, we disagree with their assumption that most lines need to be 2000 km. A total of 840,000 MW of wind power lie within 20 km of existing transmission lines. Our proposal requires the generation of only 128,000 MW of power (225,000 1.5 MW turbines in the presence of 7 to 7.5 m/s winds, giving capacity factors of 0.35 to 0.4). A reasonable portion of our required power can be obtained from turbines close to existing transmission lines. If such lines are already saturated with power, the cost of additional lines is not a cost of wind exclusively but a shared cost among all energy sources using the lines, because coal and natural gas generally do not own such lines, and therefore, do not have an exclusive right to them.

(iii) Siting almost all turbines in the Great Plains would at first glance make sense, but the larger the area that turbines are distributed over, the higher the minimum power output summed over all turbines (please see Archer and Jacobson, 2001) and the lesser the contingent backup energy required to account for a worst-case scenario for wind. In other words, if all turbines are placed in one region, a high pressure system could cause slow winds in that region. If turbines are placed in many areas of the country, the chances are slim that all regions will have slow winds at the same time.

In addition, our speculation is that most development will ultimately occur offshore, since offshore area is essentially unlimited, most people live near the coast, winds are generally faster over water than land, winds are very regular and predictable near the coast, turbines can be placed far enough out that people don't see them, and new turbines cause minimal environmental damage (the large, slow-moving turbines do not cause bird loss any more).

(Point 4) DeCarolis and Keith say, "...but to assert that the cost of wind energy is low less that of coal is not accurate. If it were, we would expect to see wind dominate virtually all new capacity installations (given the 1.5 cents/kWh tax incentives), rather than simply having the fastest relative growth rate..."

First, our paper compared the direct cost of new coal with that of new wind, not the direct cost of old coal with new wind. We concluded that the direct costs of new coal and new wind are comparable, in the 3 to 4 cents/kWh range, and this conclusion is supported by Bolinger and Wiser (2001, p. 3), who calculated the 25-year real costs of 17 wind farm proposals in California in 2001 as 3.2 to 3.7 cents/kWh, with a weighted average value of 3.6 cents/kWh. Their analysis also stated that the numbers were based on proposal information that presumably contained worst-case estimates for wind.

Second, why should wind dominate coal or gas in the marketplace when the direct costs are similar in both cases. Whereas wind receives a Production Tax Credit, coal receives a percentage depletion allowance for mining operations, deductions for mining exploration and development costs, special capital gains treatment for coal and iron ore, a special deduction for mine reclamation and closing, research subsidies, and black-lung benefits paid for by the federal government. Oil and gas (mined together) receive a percentage depletion allowance, a 15% credit for enhanced oil recovery, a deduction for intangible drilling and development costs, a "passive loss" tax shelter for investors in oil and gas, a nonconventional fuel production credit, and research subsidies.

Third, the Production Tax Credit for wind can be fully realized only if the price of wind energy exceeds the cost of wind energy by 2.5 to 3.75 cents/kWh. As such, either wind producers benefit only partially from the credit or the Credit itself drives up the price of wind. This is easily proven:

In order to fully realize the credit, the price of wind over the cost of wind must be the credit (1.5 cents/kWh) divided by the marginal tax federal plus state tax rate (40 to 60%), which gives 2.5 to 3.75 cents/kWh. Thus, if the cost of wind is 3.5 cents/kWh, the credit will be fully realized only if the price of wind is 6 to 7.25 cents/kWh (becuase the 3.5 cents/kWh cost is deductible). Wind producers are likely to optimize by raising their bid prices sufficiently to take advantage of the credit but not too high so that their projects are priced out of the selection. Ironically, then, the credit serves as a disincentive to reduce the price of wind (which is not the same as the cost of wind). A direct subsidy would be better because it would not provide incentive to maximize the difference between the price and cost of wind.

Fourth, it is commonly known that it is much easier for large producers of any product to offer a lower price, thereby having a smaller profit margin (but a larger net profit summed over all sales) than it is for a small producer, who must offer a higher price at a lower sales volume.

Finally, the market for new power plants is not a free market. In California, for example, separate bids are requested for renewable energy sources versus fossil power sources. One reason for the separate treatment is the misperception (as shown by Hirst and Hudson et al), that on a small scale, the intermittency of wind triggers an extra cost.

Footnote: The cost of HVDC lines is calculated as follows: Cavallo (1995) estimates the cost of transmitted energy through a 2000-km HVDC transmission line as 2.75 cents/kWh. This translates to 0.00138 cents/kWh/km. Cavallo assumed a capital charge rate of 0.107, which translates to an interest rate of 9% over 20 years. However, transmission lines can last 40 to 60 years. Further, commercial interest rates today are lower than 9%. These combined factors alone would reduce Cavallo's estimate by a factor of 2. Cavallo (1995) also acknowledges that the transmission line cost used was conservative and "could be about one-half what we have assumed." Changes in assumptions about interest rate, transmission line lifetime, and direct costs would change Cavallo's transmission cost estimate to 0.000345 cents/kWh/km. This estimate could be reduced further by piggybacking new lines on existing transmission powers. Nevertheless, the 0.000345 cents/kWh/km cost reaches 1 percent our estimated direct cost of wind energy (3 to 4 cents/kWh) when the average transmission line is 88 to 116 km long. Even if the average transmission line is 500 km long, the cost is still less than 5% the direct cost of wind. In the worst case (2000 km line), the cost is around 20% the direct cost of wind (0.7 cents/kWh).

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## Response to letter by Howard Gruenspecht of November 21, 2001

28 November 2001

Mark Z. Jacobson and Gilbert M. Masters, Associate Professor (MZJ); Professor (GMM)
*Department of Civil and Environmental*

We thank Gruenspecht for his comments. We will address them, below.

First, Gruenspecht makes the same point as DeCarolis and Keith, that when wind is a large fraction of the energy production, more backup energy may be needed. We addressed the issue in detail in our Response 2 to DeCarolis and Keith's response of 21 November

*Engineering, Stanford University*

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2001, so we do not repeat it here.

Second, Gruenspecht says that 10,000 km provides only 30 km of transmission per gigawatt of wind capacity. This statement is incorrect. One transmission line can transmit 2 GW of actual power = installed GW / capacity factor. For a CF of 0.36, this translates to an installed power of 5.5 GW. Thus, for 225,000 1.5-MW turbines, about 61 lines are needed, and 10,000 km / 61 lines = 163 km/line. As such, for transmission to cost <1% of direct wind cost, the average transmission line for 225,000 turbines can be up to 163 km. This number may be reduced to around 100 km/line to account for overlapping transmission during times when wind is peaking and for other factors. The 100 km/line is consistent with a number derived independently in our response to Cavallo's 21 November 2001 letter, which is based on an earlier analysis by Cavallo, who accounted for overlapping. Even if 50,000 km of transmission lines are required (500 km/line) the net cost is still <5% the direct cost of wind energy (3 to 4 cents/kWh) and <1.5% the price a typical consumer pays for electricity, which is 11 cents/kWh.

In addition, we disagree with the implication that the Siemens et al. bid of $5 billion for transmission lines out of a $15 billion project means that transmission is one-third the cost of wind energy. The transmission lines will have lifetimes of 40 to 60 years; the wind turbines, 20 years. The $5 billion investment in transmission lines will survive two to three generations of turbines. In addition, this example applies only if the transmission lines are long, which is not always necessary.

Third, Gruenspecht statement that even old coal-fired plants produce electricity at 1 to 1.5 cents per kWh direct cost appears low. Their costs are often cited as 2 to 3 cents/kWh. Regardless, the direct cost is not the cost to the U.S. citizen. The cost to the U.S. citizen is the total cost: the direct + health/environmental + subsidy cost. The health/environmental costs of old coal power plants exceed those of new coal power plants, and both far exceed the total cost of wind. Thus, our conclusion that the direct+health/environmental cost of wind is less than that of coal (whether old or new) still stands, and this is the only cost comparison that matters from a public policy point of view.

Fourth, Gruenspecht correctly states that most new capacity is natural gas. The direct cost of a new natural gas power plant is 3.3 to 3.6 cents/kWh (Office of Fossil Energy, 2001). Natural gas emits carbon dioxide, methane, carbon monoxide, nitrogen oxides, particulate matter, reactive organic gases, ammonia, and other pollutants that exacerbate global warming, urban smog, particulate health problems, acid deposition, and visibility degradation. We calculate a tentative, conservative global warming cost of natural gas as 0.7 to 1.1 cents/kWh and other health/environmental cost as 0.5 to 1.1

cents/kWh, which gives the direct+health/environmental cost of natural gas as 4.5 to 5.8 cents/kWh, more expensive to society than wind (3 to 4 cents/kWh) but less expensive than coal (5.5 to 8.3 cents/kWh). As such, we believe our conclusions apply to both coal and natural gas.

Fifth, Gruenspecht states that most black lung cases reflect past, not current, mining practices, and the number of black-lung deaths would not be appreciably impacted by the prospective reduction in coal use. This argument glosses over a real problem and misrepresents our point. First, the federal government still pays hundreds of millions of dollars per year in black lung subsidies, and miners in the U.S. still contract black lung disease by working in coal mines today. Miners, globally, contract black lung disease at higher rates. Second, the cumulative federal black-lung payments, brought to present value, are around $70 billion. The cumulative subsidy has allowed coal to gain an advantage in pricing and lobbying, and this advantage has, in turn, resulted in greater pollution output. For wind to obtain a level playing field, we argue that the federal government should spend the same $70 billion by purchasing wind turbines (or that coal should pay back the $70 billion). This amount alone would allow the replacement of 10% of coal with wind. Unlike with the black lung subsidy, the government could recoup its entire investment if it purchased turbines and sold the electricity.

References and Notes

Office of Fossil Energy, Department of Energy; see http://fossil.energy.gov/coal_power/special_rpts/market _systems/market_sys.html, 2001.