The Wedge from Substituting PV Power for Coal Power

A wedge can be achieved through substituting PV power
- for coal: 700 GW that produces 5400 TWh, or
- for gas: 1400 GW that produces 10,800 TWh

Comments for both wind and PV
The list of renewable power sources is long. It includes power from renewable energy in the form of heat that is then converted to electricity in a power cycle, as well as power that has been generated directly from an organized renewable energy source. In the first category, the heat may originate in focused sunlight or geothermal energy or the combustion of biomass. It is possible for such heat to supplement the heat from the combustion of fossil fuels, as in the co-firing of biomass and coal, mentioned briefly earlier under carbon capture and storage. In the second category, organized renewable energy, capable of being converted to electricity without an intervening thermal power cycle, can take the form of hydropower, photovoltaics (PV), wind, waves, and tides.

Here, we arbitrarily focus on the displacement only of coal and only by wind or PV. Given the assumptions in this paper, a wedge of wind must displace 700 GW of baseload coal (5400 TWh/y). Assuming a linear ramp, an increment of 100 TWh/y of either new wind energy or new PV each year for 50 years would be a wedge.

But wind blows intermittently, and PV cannot be collected at night; both are intermittent energy sources. The capacity of intermittent renewable energy to displace fossil fuel power depends on the availability of stand-alone storage and hybrid storage. A wedge is sufficiently large that it will require the wind or PV energy to be embedded in a system with sufficient storage to compensate for intermittency.

An example of hybrid storage is compressed-air wind-energy storage for remote wind farms, where the challenge is to gain maximum value from transmission lines by keeping them full. On very windy days, instead of spilling the wind at the site, the excess wind is stored in some geological formation as compressed air. Then, when winds are low, supplementary turbine power is produced by the compressed air, after its enthalpy is boosted by the burning of natural gas (S43).

For both wind and PV, deployment is measured in peak watts (W_p), a measure of the power output at the cutoff wind speed for wind and in direct sun normal to the surface for PV. We are assuming a present wind capacity of 40 GWp, based on data showing that at the end of 2002, the global installed wind capacity was 32 GW_p and had increased 29%, or 7.2 GW_p, over 2001. In 2002, 65 TWh were produced from wind, 0.4 % of total global electricity consumption (S44). Assuming the same 26% capacity factor relative to peak capacity in 2001 as in 2002[1], wind energy in 2002 exceeded wind energy in 2001 by 16 TWh, one-sixth of the linear rate of increase required for 50 years for a wedge of wind-

[1] To produce 65 TWh from wind in 2002 would require 2300 hours of operation at peak capacity, or operation for 26% of the year, assuming 28 GW_p average installed peak wind capacity.

for-coal.

A simple way to estimate intermittency, for both wind and PV, is to match peak watts to baseload watts by dividing by three. (As we have just seen, a typical capacity factor for wind or PV is about one quarter, as compared to somewhat more than three-quarters for a baseload plant. In 2054, we imagine a 30% capacity factor for PV and wind and a 90% capacity factor for baseload plants.) Thus, a wedge is about 2000 GW_p of peak wind or PV power displacing coal by 2054, or 4000 GW_p displacing natural gas. The rate of deployment, for a linear ramp, is 40 GW_p per year if coal is displaced and 80 GW_p per year if natural gas is displaced. The current global deployment of PV is about 3 GW_p. For the past several years, installed global PV capacity, like wind capacity, has been growing at 30% per year (say, 0.7 GW_p/y). Thus, a wedge of PV-for-coal requires increasing the deployment of PV by a factor of 700 by 2054, or increasing the current deployment rate by a factor of 60.

To estimate the spatial demands of future wind farms on land or in the sea, we use data for Denmark's new 160 MW Horns Rev wind farm off the west coast of Jutland (S45). This offshore wind farm has 80 turbines in an 8x10 rectangular array, each with 80m-diameter blades and 2MWp output. The turbines are seven blade-diameters apart both in the prevailing wind direction and transverse to it. Thus, each of the inner 2-MWp turbines "occupies" 310,000 m^2, and its power density is 6 Wp/m^2, from the perspective of surface area required[2]. A wedge in the form of 2000 GWp of wind-for-coal would then require 30 million hectares of surface. If all were on land, this would be between one and two percent of the world's 1800 million hectares of land estimated to have winds of Class 4 and above (S46). Thirty million hectares is also 3% of the land area of the United States. Land from which wind is harvested can be used for many other purposes, notably for crops or pasture.

The land demand for PV is inversely related to the conversion efficiency of sunlight. Here we choose 100 W_p/m^2 for the peak power output from PV divided by the area of the collection site[23], 15 times greater than for wind. Then, a wedge in the form of 2000 GW_p of PV-for-coal requires two million hectares, or 20,000 km^2, of site surface, either dedicated land or multiple-use surfaces such as the roofs and walls of buildings.

Note that in quantifying the wedges of renewable electricity, here, we have not needed to take into account the mix of centralized and distributed generation. Hundred-square-kilometer regions devoted to arrays of photovoltaics or wind farms have been treated as equivalent to large numbers of rooftop PV units or isolated wind turbines.

[2] The area occupied by the entire Horns Rev wind farm is reported as 20 km^2 (S45), which results in a ratio of peak-power production to wind farm area of 8W_p/m^2. The area reported is equal to nine times seven inter-windmill spacings, rather than ten times eight, as if no surface were "occupied" beyond the perimeter of the wind farm.

References

S43 Cavallo, A.J., 1995. “High-capacity-factor wind energy systems,” *J. Solar Energy Engineering*, 117:137-143.

S44 Website of BP on wind energy: http://www.bp.com/genericarticle.do?categoryId=117&contentId=2001227. Accessed April 12, 2004

S45 Website, “Horns Rev Offshore Wind Farm.” http://www.mumm.ac.be/Common/Windmills/SPE/Bijlage/1%20%20Horns_Rev_brochure.pdf**.** Accessed July 11, 2004

S46 Grubb, M.J., and N.I. Meyer, 1993. “Wind energy: Resources, systems, and regional strategies.” In *Renewable Energy: Sources for Fuels and Electricity,”* T.B. Johansson et al., eds. Washington, D.C.: Island Press. Table 9, p. 197.