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Wind Energy Contribution to a Low-Carbon Grid

Wind power systems being promoted today contribute little to a low-carbon grid because the system concept is 70–90 percent dependent on dispatchable fossil fuel generators. This structural conflict has no visible solutions.

Alex Pavlak

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President Obama proposed a strategic goal for greenhouse gas emissions: an 83 percent reduction of CO_2 emissions below 2005 levels by 2050.[1] This is a good strategic goal, a good end state. Big CO_2 emission reductions are necessary if we are going to halt global warming. The goal is technically feasible. France has shown that we could achieve an 80 percent carbon-free grid in 40 years (2050) using nuclear power if we chose to do so. Eventually we would like to have an electric power grid that is substantially carbon-free and sustainable.

Given the strategic goal, disciplined systems engineering procedure calls for the engineer to conduct a strategic scenario analysis to clarify a feasible set of choices for achieving the goal. The client (President, Congress and the American people) then choose a direction. Engineers then develop a plan with milestones by which we can measure progress towards achieving that strategic goal. With disciplined development, funds are not committed to brick-and-mortar production systems without a high degree of confidence that the investment will contribute to the strategic goal.

This article attempts to take a strategic view of wind energy by exploring the extent to which wind energy can contribute to a low-carbon grid.

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I. Misguided Goals: Renewable Portfolio Standards

Disciplined systems engineering starts with a purpose, a strategic goal, an end state. An example of such a goal would be to build a 100-story skyscraper. Engineers then follow a process, a set of best practices, to prepare an engineering plan. Milestones can be derived from the plan. One milestone might be to complete the first 20 stories by a certain date.

Clean energy systems are being engineered by politicians, lawyers, and lobbyists who reverse the logic. The goal is to build the first 20 stories by a certain date and we will worry about designing the whole building later. There is no assurance that the first 20 stories will support the next 80 stories. This logic is called a renewable portfolio standard (RPS).

A variety of governments have established RPS targets such as 20 percent wind by 2024 under the mistaken impression that wind is carbon-free. Wind turbines are carbon-free but the wind system is 80 percent dependent on dispatchable (available-on-demand) fossil fuel generators. RPS are not strategic goals, they are not end states. Once the RPS goal is achieved we cannot stop. We need to move beyond 20 percent to reach 83 percent. It would be most unfortunate if the only way to do that would be to remove what has been installed and proceed in a different direction. Everything we do should be tested against its ability to achieve the strategic goal.

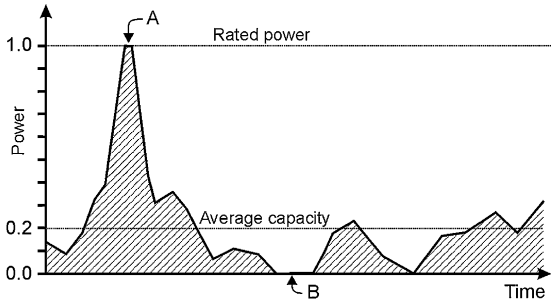

Figure 1: Single 1 MW Wind Turbine Production

Figure 1 illustrates the conceptual power output from a single 1 MW wind turbine. The vertical axis is power production and the horizontal axis is time, spanning perhaps 10 days. The fluctuations are the result of major weather patterns.

Manufacturers design wind turbines to have a maximum continuous power capability. Large wind turbines are designed to produce full rated power when the wind equals or exceeds its rated threshold. This produces the flat response at rated power as illustrated by A in Figure 1. Likewise, wind turbines have a cutoff wind velocity and shut down when the wind drops below a low level, as illustrated a point B in Figure 1.

Average capacity of a wind turbine is the average power production level over a long period of time, perhaps a year. Average capacity depends on wind turbine design and wind speed at a specific site. Good, fairly windy sites result in an average capacity of 20 percent. Wind turbines have short periods of enormous power production corresponding to storms and weather fronts and extended periods of low production corresponding to high pressure (low wind) weather patterns.

II. Simple System Scenario with Level Load

The number of wind turbines that can be installed in a power system is limited by curtailment. If a storm comes through in the middle of the night when demand is low, wind production can exceed demand and it is necessary to shut down wind turbines and dump power. Wind production is curtailed.

Curtailment can be minimized by leveling the load, managing the demand so that it is constant with time. France achieves a diurnal (daily) level load by requiring everyone to have large electric hot water heaters controlled by the utility. The utility charges the nation's hot water heaters at night. They also use pumped hydro storage. Level load is the goal of the Smart Grid and an optimistic assumption. The system works better with level load. Level load assumes that the Smart Grid, plug-in

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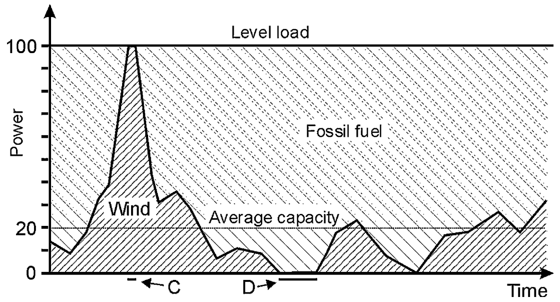

Figure 2: Simple System Scenario with Level Load

electric vehicles, and other technologies all work as advertised.

Now consider a simple electric power system with level 100 MW load. We could deploy a single wind farm with 100 of the previously described 1 MW wind turbines to result in the system power profile illustrated in **Figure 2**. The wind production profile would be simply 100 times larger than that of a single wind turbine in Figure 1.

With a 100 MW load and 100 of the 1 MW turbines, the rated capacity is the same as the system load. When the wind is blowing hard the system gets 100 percent of its power from wind, as illustrated by the time period C. Likewise when there is no wind blowing the system gets 100 percent of its power from fossil fuel generators, as illustrated by the time period D. The average capacity of wind remains at 20 percent so that on average the system gets 20 percent of its energy from wind and 80 percent from fossil fuel. This is called 20 percent wind penetration.

Wind penetration is the average percentage of power demand that the system gets from wind. An optimal wind system design (level load and closely located wind farms) has enough wind turbines so that wind penetration is equal to the average wind capacity. If we had fewer wind turbines, maximum wind production would be less than load. If we had more wind turbines, maximum wind production would exceed load and would have to be curtailed.

III. Widely Distributed Wind Farms

One way to increase the system wind penetration is to expand the transmission system to connect widely dispersed wind farms. **Figure 3** shows the conceptual impact of wide wind farm dispersal versus a single central location (dashed line). The average capacity for the system does not change if we still have the same number of wind turbines each with the same average capacity.

Studies[2] using wind data simulated from real meteorological conditions have shown that one impact of connecting widely dispersed is to smooth the curve, with lower ramping rates. Another impact is to reduce the peaks E and fill the troughs F in Figure 3. The reason for this is that it is unlikely that all the wind turbines will be operating at rated capacity at the same time. Also, it is likely that some wind will be blowing somewhere. The large fluctuation features, the result of large-scale weather patterns, would still exist. These large-scale features result from high and low pressure meteorological areas and weather fronts. The major weather features can be continental in scale.

A recent study (EWITS[3]) looked at the feasibility of integrating wind on the Eastern Interconnection. This is a synchronous power area that includes the eastern United States, eastern Canada, and the Midwest (excluding Texas). They did a good job modeling wind resource and characterizing the transmission infrastructure

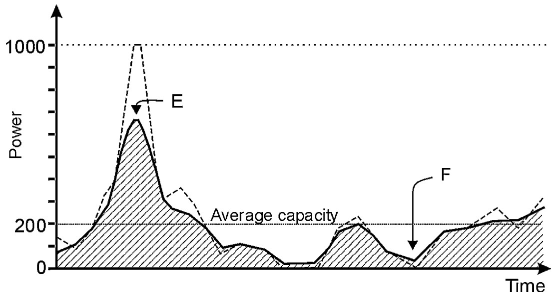

Figure 3: Qualitative Impact of Widely Dispersed Wind Farms

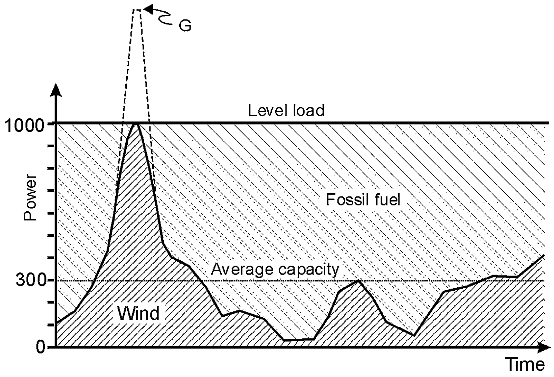

Figure 4: Conceptual System with Widely Dispersed Wind Farms

necessary to transmit wind-generated electricity from the Midwest to the East Coast.

EWITS suggests that with long-distance transmission, widely dispersed wind farms could potentially increase wind penetration to 30 percent. The way this works is conceptually illustrated in **Figure 4**. Since peak production has been decreased by one-third, we can increase the number of wind turbines by 50 percent without curtailment. The rated capacity of wind is now 50 percent above the load (point G on Figure 4) but since all the wind turbines never produce at rated power at the same time, this does not result in curtailment. Optimistically, connecting widely dispersed wind farms might increase penetration from 20 percent to 30 percent. But this still leaves the system 70 percent dependent on dispatchable fossil fuel generators.

IV. Wind Backup Generator Technology

Backup generators for wind need to be dispatchable (available on demand), and need to start and stop quickly to respond to rapidly changing wind fluctuations. The technology of choice today is fossil fuel – natural-gas-fired Brayton cycle gas turbines (essentially, natural-gas-fueled jet engines).

There are not many options for dispatchable zero-carbon generators. Hydro is potentially dispatchable and there is an excellent opportunity for integrated wind-hydro. But there is not enough hydro resource for large-scale deployment.

There are three potential zero-carbon baseload generator technologies: nuclear, coal gasification with carbon sequestration, and natural gas combined cycle with carbon sequestration. To achieve high efficiency, all three technologies involve Rankine cycle steam engines with large boilers. These boilers have too much thermal inertia to respond quickly to wind fluctuation. Forcing coal to respond quickly ends up emitting more CO_2 than steady operations. It is like driving a car in stop-and-go-traffic rather than at steady highway speed. Many wind studies ignore this incompatibility. There is no visible alternative to dispatchable fossil fuel generators to back up wind systems.

V. 83 Percent Carbon-Free Scenario

The dispersed wind farm system just described is 30 percent carbon-free. But the strategic goal is 83 percent carbon-free. Based on what we know today, an 83 percent carbon-free scenario will require zero-carbon baseload generators. They can be either nuclear or fossil fuel generators with carbon sequestration.

Figure 5 presents a conceptual system with level load and three generator types: wind, a dispatchable fossil fuel generator, and a zero-carbon baseload generator. Since the system

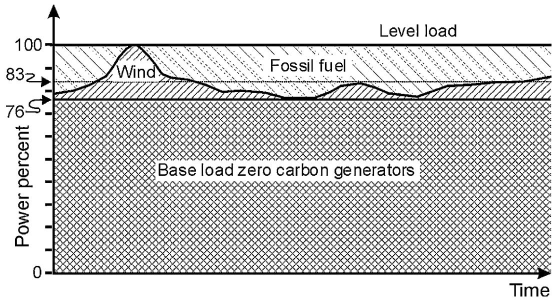

Figure 5: Conceptual 83 Percent Carbon-Free Electrical Power System

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requirement is 83 percent carbon-free, 17 percent of the average system power can come from dispatchable fossil fuel generators. Assuming dispersed wind turbines with 30 percent average capacity (hence 70 percent fossil fuel), then the allowable 17 percent fossil fuel can support 7.3 percent wind (17 percent × (30/70) = 7.3 percent). The resulting conceptual system is illustrated in Figure 5. 76 percent of the energy comes from baseload, 7 percent from wind, and 17 percent from dispatchable fossil fuel.

This relationship can be generalized in **Figure 6**. The assumptions are level load, no curtailment, and all available fossil fuel generators configured to back up wind. There are two curves for two average wind capacities. Average capacity is increased from 20 percent to 30 percent by long-distance transmission capability.

It is clear from Figure 6 that there is a maximum wind penetration level when penetration reaches average capacity. Beyond the peak, wind needs to be curtailed because there are not enough fossil fuel generators to back up the wind.

The strategic goal is an 83 percent reduction in carbon emissions. Wind technology as being promoted today can make little contribution to achieving this goal.

VI. The Future of Wind Energy

Based on what we know today, wind energy is not a strategic solution. EWITS has shown that wind cannot provide a large amount of power to a low-carbon grid because it is 70–90 percent dependent on dispatchable fossil fuel generators.

In disciplined systems engineering, a decision to deploy a technology is made only if that technology is consistent with the strategic goal. While enthusiasts acknowledge the idea that wind energy is not compatible with the strategic goal, they argue that something will change over the next 40 years. For conservative clients, that is not good enough to justify deployment. Most clients require demonstrations to show that the barrier is not a structural conflict, evidence that a solution exists.

One development direction is low-cost grid scale storage: batteries, compressed air, pumped storage, or something novel. But the magnitude of the required storage is enormous. The challenge is not just level diurnal load fluctuations but to store large amounts of energy on time scales associated with major weather patterns (several days). While nothing has been shown to be cost-effective, this direction warrants research and development. Note that storage for wind is different than storage for solar and tides. Solar positively correlates with load and has a diurnal timescale; tidal currents run four times per day.

Another direction would be to invent integrated subsystems where wind is coupled with dispatchable carbon-free generators. One barrier is the incentive for the zero-carbon backup system to participate in such a subsystem. There is no incentive for baseload coal gasification with carbon sequestration or nuclear power to add cost to back up wind. If we have zero-carbon baseload generators, why have wind?

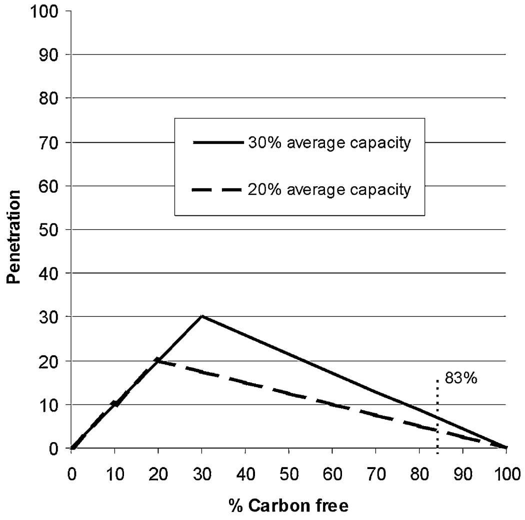


Figure 6: Wind Penetration as a Function of System Emissions

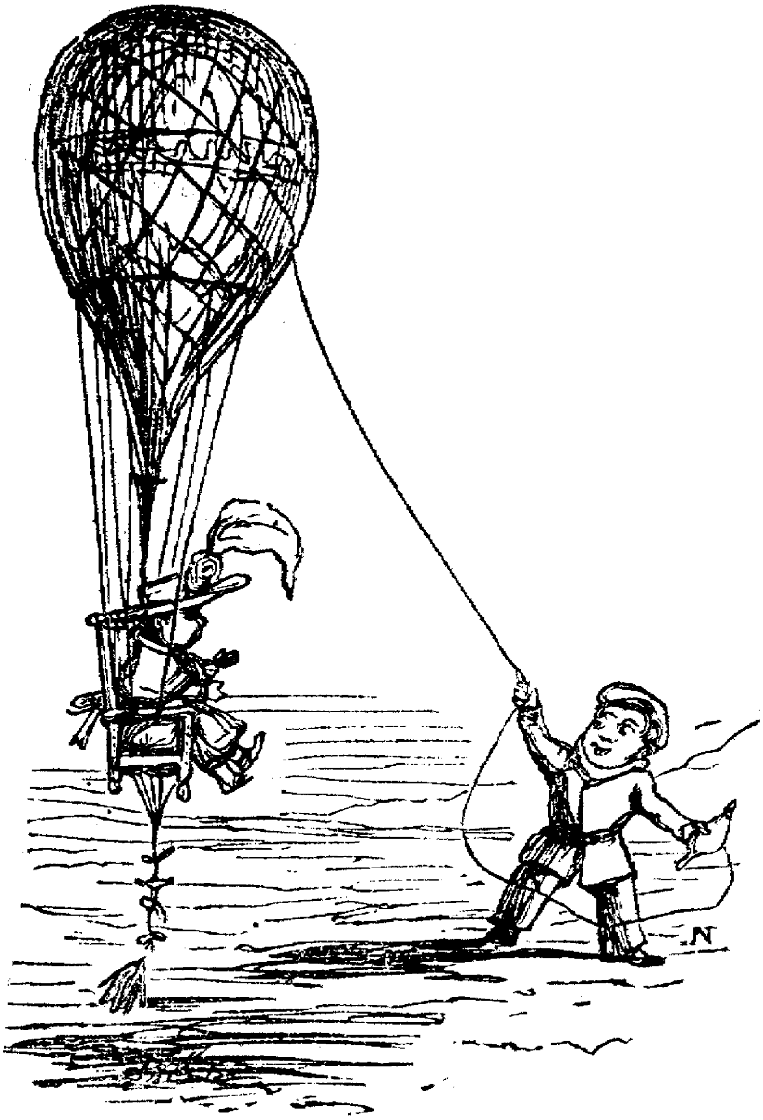
There are niches, opportunities to invent novel subsystems whereby wind is coupled with an intermittent tolerant load. Water pumping is a classic example. Another possibility is wind-powered water desalinization.

Wind energy does have a role as a zero-carbon low-cost interim solution for a power grid that is still dominated by fossil fuel generators. Wind farms can be installed quickly and cost is low at exceptionally windy sites.

VII. Summary

This article develops strategic scenarios to explore the extent to which wind can contribute to a low-carbon grid. The wind system concept being promoted today is to plug wind farms into the electric power grid. The grid needs to accommodate fluctuations and provide power when the wind does not blow. Within this concept there is an optimal wind penetration (the percent of average demand that can be supplied by wind). A natural balance occurs when wind penetration is equal to average wind capacity (average wind production divided by potential rated wind production). A typical number is 20 percent. Adding more wind turbines results in curtailment, dumping power because it is not needed. Since the grid requires power when there is no wind, the grid is 80 percent dependent on dispatchable (available-on-demand) fossil fuel generators. This article shows that while wind might contribute 20 percent of the power to a grid that is 20 percent carbon-free, the contribution is only 4-7 percent to a grid that is 83 percent carbon-free.

Based on what we know today, wind energy is not a strategic solution (end state) for low-carbon electric power. Disciplined system development might view wind energy as an interim low-cost option.■



The grid needs to accommodate fluctuations and provide power when the wind does not blow.

Endnotes:

1. White house press release, President to Attend Copenhagen Climate talks, Nov. 25, 2009, at http://www.whitehouse.gov/the-press-office/president-attend-copenhagen-climate-talks.

2. U.S. Dept. of Energy, *20% Wind Energy by 2030: Increasing Wind Energy's Contribution to the U.S. Energy Supply*, DOE/GO-102008-2567, May 2008, at 91.

3. David Corbus *et al. Eastern Wind Integration and Transmission Study*, NREL/SR-550-47086, Jan. 2010, at http://www.nrel.gov/wind/systemsintegration/pdfs/2010/ewits_executive_summary.pdf.

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