Using electric vehicles as storage for large offshore wind power

by
Willett Kempton (willett@udel.edu) and
Amardeep Dhanju (amar@UDel.Edu)
College of Marine Studies, University of Delaware, Newark, DE 19716, USA

21 August 2005
Presented at: Copenhagen Offshore Wind 2005

Abstract

Offshore wind now appears to be a huge resource--sufficient to provide most of the electricity for many of the world's heavily populated coastal states. This long-term resource promise may be constrained because wind's power fluctuations lead to grid integration problems. At small scales of wind implementation, existing mechanisms of grid regulation are sufficient. However, existing mechanisms cannot support wind at the penetration levels needed to, for example, meet British or Danish renewable energy targets or to make a significant impact on CO2 emissions. Storage has been proposed as a solution, but dedicated storage adds significant cost to wind power. This paper reviews existing storage technologies, and then proposes vehicle-to-grid power (V2G) as a storage resource for large-scale offshore wind power. V2G uses the distributed storage inherent in electric-drive vehicles (here we consider battery and plug-in hybrid vehicles) to stabilize wind generation. We model large-scale wind with V2G storage based on prototype V2G electric vehicles already built. These vehicles charge from the grid and discharge to the grid at 15 kW, with storage of 30 kWh; incremental capital cost to add V2G is approximately € 400 (€22/kW or US$33/kW). Using two different models as a cross-check, we calculate that wind generation meeting 50% of electrical energy needs could be stabilized by 8 - 38% of the vehicle fleet with V2G capability. Since offshore wind sites are often near cities with large vehicle fleets, V2G offers an exceptionally low-capital-cost means of simultaneously stabilizing wind power and reducing petroleum needs of the light vehicle fleet. Prototype vehicles with this capability (at 20 kW/vehicle) have been built, driven and provided charge or discharge on signal from the grid operator.

Keywords: large scale wind; wind storage; V2G; electric vehicles

1. Introduction

Recent global wind power assessments estimate that economically-exploitable world wind resources are 72 TW, compared with current electricity demand of 1.8 TW (Archer and Jacobson 2005). This good news of the abundance of resource comes just as the bad news realization of the breadth and speed of climate change effects is beginning to terrify knowlegable readers of the scientific literature. A large displacement of carbon from the electricity generation sector, the largest carbon source in many OECD countries, now appears practical from the standpoint of the resource size of wind. A large expansion of wind power appears economically and technically feasible, as the machines are available, are rapidly being improved, and are already cost-competitive in many regions given modest policy incentives. However, large-scale wind, say, over 20% of capacity, is not yet practical from the standpoint of grid integration. Here we focus on that problem.

The wind fluctuates in strength, on time periods from seconds to seasons of the year. At low wind penetrations prevalent today in all OECD countries but Denmark, existing mechanisms to handle existing fluctuations are adequate. Denmark's current 20% is manageable in part because of the large Scandinavian hydro resource, whose power can be switched quickly to compensation for fluctuations in wind power output. Existing mechanisms, mainly control of fossil and hydro generators, can be used to adjust for wind fluctuations. Wind's fluctuations can be greatly reduced by geographical distribution (Geibel 2000; Archer and Jacobson 2003; DeCarolis and Keith 2004 or 2005), a strategy not yet fully quantified. Nevertheless, as wind grows as a proportion of generation, separate mechanisms will need to manage wind's fluctuations. There are two basic approaches—backup generation, and electricity storage.

Toward the end of making possible very large-scale wind power, this paper reviews the options for backup and storage, and presents a new storage option for large-scale wind power. The new storage option would use the anticipated development of an electric-drive vehicle fleet (battery vehicles, plug-in hybrid vehicles, and possibly fuel-cell vehicles). All these vehicles have within them the ability to store energy that can be converted to grid-compatible power, because that storage is necessary for driving. Although design of some vehicles have envisioned recharging them from the electric grid (power from grid to vehicle), we add the concept of "vehicle to grid" power, or V2G, that is, making an electric vehicle capable of two-way power interchange with the electric power system.

Concepts of Storage and Backup and Storage for Wind Power

From an electric utility perspective, wind alone is an intermittent electrical generator, but with storage or backup added, wind can become base load power. Storage and backup are distinguished as follows. Backup provides power when the wind is insufficient to meet demand; it is idle when the wind is sufficient or excessive. Storage similarly provides power when wind power is below demand, but it additionally stores when wind power is excessive.

An illustrative wind profile is given in Figure 1. This figure is modified from a figure in Denholm, Kilsinksi and Holloway (2005), to show only the wind power output. The capacity of this hypothetical installation is about 900 MW, but Figure 1 shows that most of the time, it runs at less than that level of power.

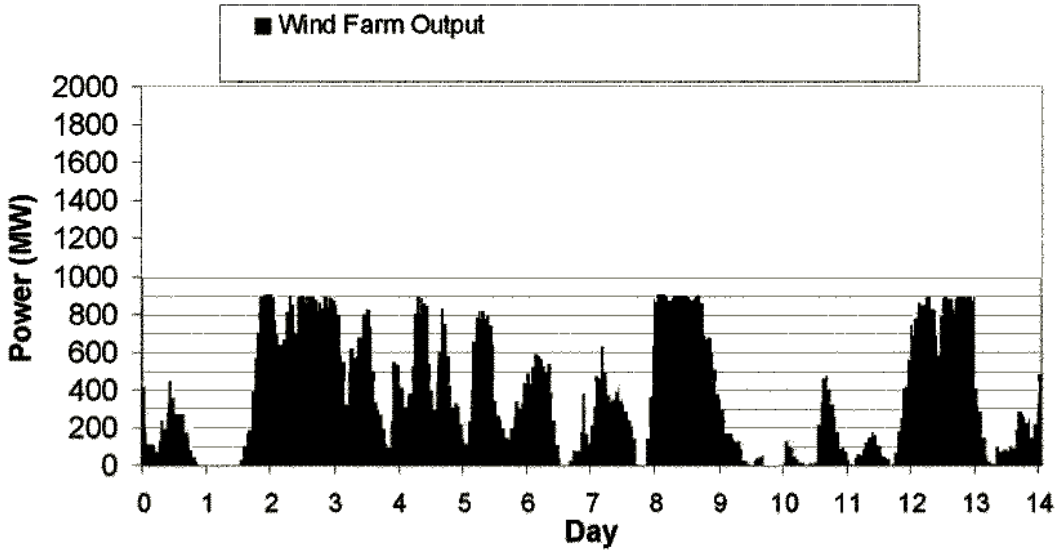

Figure 1. Wind output fluctuates without storage or backup. This figure illustrates a wind farm of capacity of 900 MW (modified from Denhold, Kulcinsis and Holloway 2005).

To give a quantitative illustration of how the fluctuations in Figure 1 might be dealt with, we assume an isolated wind plus backup or storage system, with the goal of producing steady power from the combined system. As a simplified illustration to quickly compare backup with storage, we assume a 33% capacity factor and a constant load equal to the wind capacity.

Beginning our quantitative illustration with a backup strategy under these simplified assumptions, we would size the backup power to match the capacity of the wind power. If the maximum wind output were 900 MW and the load were 900 MW, the backup generator would also be 900 MW. On the rare occasions of so much wind that the wind generators are producing full rated power, the backup would be completely off. Most of the time, the wind would be producing less than 900 MW, sometimes zero power, and the backup generator would produce the balance needed to meet the demand hypothesized to be 900 MW. The backup generator uses another energy source, typically fossil fuel. In Figure 1, this would be seen as backup "filling in" the valleys under 900 MW.

Another option for backup is to size the wind over the required power of 900 MW—this would not reduce the needed backup capacity of 900 MW, but would reduce the running time of backup and thus reduce its CO2 emissions. Also, when more wind power is generated than needed, the excess is wasted, or in wind industry jargon, "spilled."

By contrast, a storage strategy would size the wind to meet the average load requirement. Thus, to perform an average energy output of, say, 900 MW, one would need a wind facility with peak capacity of 2,700 MW (assuming 33% wind capacity factor and large storage). When the wind power is above demand, the storage is being filled. When it is below demand, the storage is being discharged in order to meet electrical demand. This is clearly preferable from an environmental standpoint, as wind, rather than fossil fuels, is being used to produce all the power. (Assuming that the storage technology does not use fossil fuels.) From an economic standpoint, the optimum depends on the relative costs of wind, backup, and storage, the value of maintaining steady output, and the value or credit for low emissions.

The storage strategy is diagrammed in Figure 2, from Denholm, Kilsinksi and Holloway (2005). In this example, the target output is a constant 900 MW, a challenging 47% of the 1900 MW installed wind capacity. This is the same wind profile as shown in Figure 1, but now, much of the excess above 900 MW demand is stored (red in figure, or see key if printed as grey scale); only if the storage is filled does the wind need to be spilled (green in figure). When wind is insufficient, the stored energy fills in to meet the 900 MW criterion (yellow in figure), but during long periods of low wind, the storage can be exhausted, causing the system to fail to meet projected demand. At such times when storage is emptied, either other generators on the grid would be activated, or load would have to be curtailed. Of course, the relative sizes of wind and storage, and the contracted minimum, can be adjusted, depending on their relative costs and the allowed frequency and duration of under-power times.

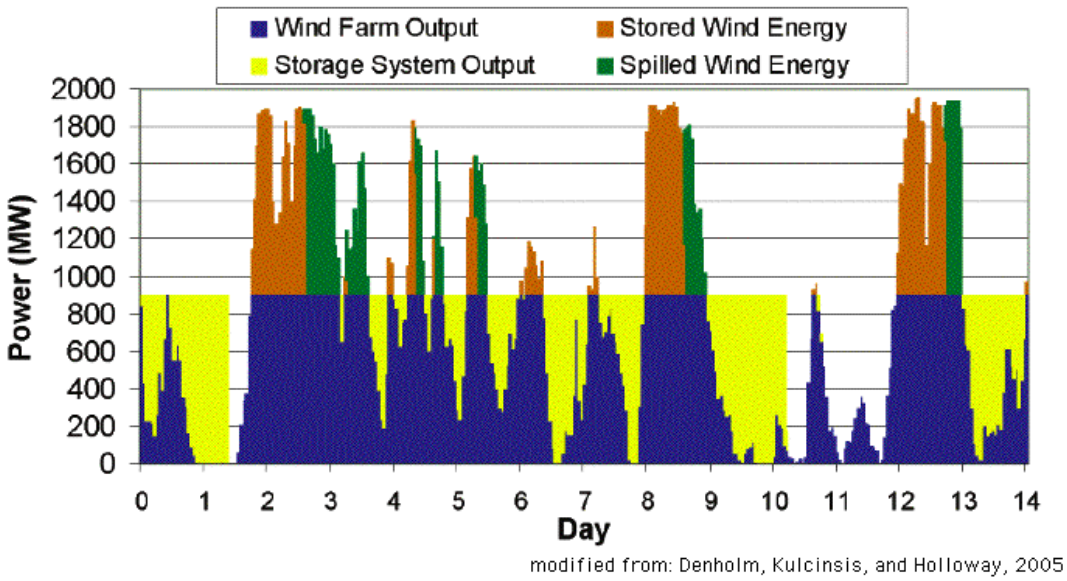

Figure 2. Wind with storage, approximating constant 900 MW output, from: Denholm, Kilsinksi and Holloway (2005).

Other than leveling output, the storage also provides additional benefits. As described by (Schoenung et al., 1996, p358), these can be classified as capacity, dynamic and strategic benefits. Capacity benefits accrue when energy storage allows utilities to defer or avoid otherwise needed additions of central peaking generation capacity, bulk transmission, or local distribution. Dynamic operating benefits are achieved using energy storage to optimize several important aspects of utility electric supply such as load following, spinning reserve, and the regulation or correction of frequency, voltage, and power factor. Finally, the strategic benefits from the energy storage can reduce uncertainty in providing energy supply. Research by EPRI indicates that energy storage can reduce uncertainty in providing energy supply such that the overall value of storage on a per-MW basis is 40% greater than other generating alternatives (Schainker 1990, as cited in Schoenung et al., 1996).

The two approaches of storage and backup can be combined. For example, if a smaller storage is provided, slow ramp-up backup can be provided to fill in the end of extended wind gaps, like those shown in Figure 2. In this case, the storage

provides a long lead time prior to need for the backup, thus allowing use of slow ramping backup generators.

Existing fossil fuel generators, especially fast response ones like natural gas and hydroelectricity, can be used for backup to wind. Existing storage technologies that have been used at an electric utility scale include pumped hydro, large batteries, and compressed air energy storage (CAES). But, before we resign ourselves to the costs of building storage or backup dedicated for intermittent wind power, we should first ask, "Is there any unused storage already in the system?" Suprisingly, the answer to that question is, "Yes, there is. Quite a bit, actually." The existing storage, as first pointed out by Kempton and Letendre (1997), is in the light vehicle fleet. This is currently in the form of liquid fuel combusted to turn a shaft, which is of little value to electric utilities. However, the emerging electric drive vehicle fleet (battery, hybrid, and/or fuel cell vehicles) produce alternating current onboard, typically a very clean sinusoidal wave form, and at very small incremental cost the existing power electronics in these vehicles can be set to produce 50 Hz or 60 Hz AC.

V2G as backup and storage

How are electric vehicles used for backup or storage of wind power? First, we assume that there is a plug on the vehicle, connecting it to the end of the distribution grid when parked. This plug is required for battery vehicles and plug-in hybrids (PHEV), but could be added for fuel cell vehicles. Kempton, Tomic, Brooks, Gage, Cocconi and colleagues have conducted extensive analysis of the engineering and economics of this configuration. The short version of the engineering is that a high-power connection is practical (10 – 20 kW), line frequency and interconnect standards can be met (Kempton et al 2002; Gage 2003, Brooks 2002). Capital costs are incurred by adding circuitry to synchronize to the grid, for controls, and for protection from energizing a dead line. A power controller can now be purchased with V2G capability from AC Propulsion, which has a 20 kW line connection at 208/240 V AC. The same company is prototyping vehicles for small-scale production with 30 kWh Li-ion batteries and this 20 kW two-way power line connection[1]. They report that the incremental capital cost to add V2G was approximately €400 per vehicle, which is less costly than other storage options on a per kW capital cost basis (22 €/kW or US$33/kW).

Kempton and Tomic derive formulas to calculate operating costs for V2G storage. Whereas capital costs are easy to tabulate and are quite small, operating costs (per kWh) depend on equipment and operating assumptions (2005a). The short version of the economics, in terms of existing electric markets, is that V2G for regulation services are highly competitive for battery vehicles, spinning reserves is economical for either battery or fueled vehicles, longer-term operating reserves may be profitable for fueled vehicles, bulk power is not economically competitive (price per kWh is too high), and peak power may be competitive (Kempton et al 2002; Kempton & Tomic 2005a).

Operationally, private vehicles are in use 1 hour/day, parked 23 hours/day (in the US; time driving is less in other OECD countries, e.g. Kempton and Kubo 2000). Depending on parking locations, that means that vehicles could potentially be

[1] For technical specifications, see www.acpropulsion.com. The controller with V2G built-in is the AC150, Rev 2.

connected to the electric grid most of the day. Fleet vehicles are typically parked 18 h/d, which is quite useful, and are typically parked in one location that entire time (Tomic and Kempton, n.d.). From a driver needs perspective, V2G controls would be provided for the driver to limit any drawdown, or even to request fast recharge (Kempton and Tomic 2005b).

In terms of wind power support, V2G backup can be provided by the fueled vehicles (fuel cell and hybrid running motor-generator). Storage can be provided by the battery vehicle and the plug-in hybrid running V2G from its battery. Could hydrogen-powered fuel cell vehicles be considered electrical storage, if the hydrogen is produced by electrolysis? Because of round-trip losses of conversions in the path electricity-electrolysis-hydrogen-storage-small fuel cell-electricity—approximately 75% losses for electrolytic hydrogen versus 25% for battery (Bossel 2005)—round-trip electrolytic hydrogen appears to be too inefficient to be practical as storage.

The suitability of these three types of vehicles for storage versus backup is laid out in Table 1. The table also represents another difference, that some vehicles are better for shorter-term markets, like regulation and spinning reserves, others are better for longer term markets, like non-spinning reserves.

Table 1. Suitability of different vehicle types for wind power storage versus backup, and for differing electric markets.

Vehicle type	Wind function		Electric markets		
	Backup	Storage	Regulation	Spinning Res.	Non-spinning res.
Battery		++	++	++	
Plug-in hybrid	++	+	+	++	++
Fuel cell	++				++

National comparisons of V2G potential

Given the type of V2G vehicles that have been built, and assuming a maximum electrical plug connection of 15 kW (220 V at 70 Amp), we can calculate the potential power of V2G in comparison to electrical loads in several OECD countries. This comparison is shown in Table 2. The first column of Table 2 gives the size of the light vehicle fleet in each country, and the second column calculates the power that would be produced if each of these vehicles were plugged in and providing 15 kW to the grid. For example, in the second row, Denmark, we see that the country has about 1.9 million cars. If each were producing 15 kW, that would be 28 GW. The fifth column is the average electrical load of Denmark, 4.9 GW, so the full vehicle fleet at 15kW would produce 788% of the average load. As a more realistic number, we assume that 25% of the fleet would have V2G and be available at the time needed, and we assume a longer wind lull, say, 2 – 3 hours, of no wind at all so that power would be limited by the charge on the battery the driver is willing to draw down at that hour. Under these more modest assumptions, shown in the fourth and final columns, the Danish vehicle fleet would provide 2.4 GW, which is 65% of the country's load.

Table 2. The V2G potential of the light vehicle fleet, compared with load, in 11 countries.

Country	Number of Passenger Vehicles (a)	100% of cars, V2G @ 15 kW (GW)	25% of cars, V2G @ 5 kW (GW)	Average Load for (GW) (b)	100% of cars @ 15 KW / Average Load (%)	25% of cars @ 5KW / Average Load (%)
USA	191,000,000	2,865	239	417	686	57
Denmark	1,900,370	29	2.4	3.6	805	65
UK	28,447,908	427	36	40	1,081	91
Germany	44,652,517	670	56	58	1,149	96
Italy	33,819,390	507	42	34	1,473	122
Ireland	1,470,644	22	1.8	2.6	846	69
France	29,218,210	438	37	50	885	75
Spain	18,714,180	281	23	26	1,068	87
Portugal	5,807,664	87	7.3	5.0	1,740	146
Netherlands	6,865,832	103	8.6	12	888	74
Sweden	4,050,273	61	5.0	15	407	33

Table notes:

(a) Passenger car counts for EU Countries are derived from per capita vehicles (source a.1) multiplied by country population (source a.2):

(a.1) Passenger Car per 1000 inhabitants 2002, Eurostat/ DG TREN, viewed 12 September 2005, http://epp.eurostat.cec.eu.int/portal/page?_pageid=1996,39140985&_dad=portal&_schema=PORTAL&screen=detailref&language=en&product=Yearlies_new_transport&root=Yearlies_new_transport/G/eba12048

(a.2) EU population Figures 2003, Eurostat/ DG TREN, viewed 12 September 2005, http://epp.eurostat.cec.eu.int/portal/page?_pageid=1996,39140985&_dad=portal&_schema=PORTAL&screen=detailref&language=en&product=Yearlies_new_population&root=Yearlies_new_population/C/C1/C11/caa10000

(a.3) US Number of passenger vehicles data for year 2001, EIA, viewed 18 September 2005, http://www.eia.doe.gov/emeu/rtecs/nhts_survey/2001/tablefiles/table-a01.pdf

(b) From World Total Net Electricity Consumption 1980- 2003, EIA, viewed 14 September 2005, http://www.eia.doe.gov/pub/international/iealf/table62.xls. Load data is for year 2003. Source was in Billion KWh /year, here divided by 8760 h/y to yield average GW.

It should be apparent from the quick calculations in Table 2 that the V2G power potential is very large, but not unlimited. For example, how would this large storage resource in V2G be scheduled within typical electrical generation dispatch, in which plants are turned on and off, allowing that different plants require differing startup times and have different costs per MWh? We next calculate more precisely the amount of wind power that would be enabled by a large V2G fleet.

Our calculations use the US as an example, but the results is expressed in % of the vehicle fleet, so the results can be approximately scaled to other OECD countries by using the comparison data in Table 2. As an example, we calculate for wind providing 1/2 of total US electrical energy.

Some textbook treatments of wind describe storage as if it would be built and dedicated to match wind installations and their fluctuations (Manwell et al 2002). But this mechanistic dedicated storage approach does not reflect the ways in which electrical grids are already set up to handle intermittency problems (power plant failures, fluctuations in load, etc). Roughly speaking, fluctuations at intervals of

minutes are covered by the electrical power market knows as "Ancillary Service, Regulation," failures at the several minute levels are covered by spinning reserves, and longer term failures or unexpected needs are met by non-spinning reserves, other operating reserves, and by the hourly energy markets.

Apart from time intervals, one must also choose storage in part based upon geography and transmission capacity. Most cars are in cities. Since humanity has built heavily on the world's coastal areas, V2G is typically within a few kilometers, at most a few hundred kilometers, of offshore wind sites on the continental shelves. On the other hand, large mid-continental wind resources, such as those of Mongolia and the Great Plains in North America, are distant from most population. For remote wind sites that require dedicated transmission, storage may be optimal at the wind site, because storage there not only smoothes out wind power fluctuations but also improves capacity factor of the power lines (Cavallo, 1995). Typically, V2G does not help with capacity of transmission lines from remote wind sites, as most vehicles are located close to loads.

Calculating how much V2G is needed to integrate large scale wind[2]

To quantitatively estimate the storage needs in terms of electric markets, we turn to the few existing studies of the impact of large-scale wind upon the grid, which consider regulation and operating reserves. Then, as a check on those calculations, we develop our own estimate of storage capacity needed for large-scale wind.

For regulation, wind power increases the need over today's regulation needs. This added need for regulation has been estimated in prior studies, showing a range of estimates. Hirst and Hild (2004) simulate a large wind fraction (2.6 GW capacity in a 4.5 GW generation utility) in dispersed sites. They find the need for regulation to be 0.5% and for load following to be 7.3% of wind capacity (1.6% and 21% of average output, p 32). Hudson et al (2001) estimate regulation need of 11% for small and 6% for large single wind installations. In the following table, we will use the Hudson et al 6% figure to estimate regulation requirements, although this is probably too high.

US electric utility capacity is 811 GW (utility plus nonutility, EIA 2001) at 57% capacity factor. To generate half of the electrical energy from wind, at 33% capacity factor (Kempton, Firestone et al 2005), would require 700 GW of wind capacity (thus average wind output of 231 GW). Regulation at 6% would be 42 GW, which could be met by 2.8 million battery vehicles at 15kW regulation per vehicle, or 1.6% of the US fleet (Table 2). Assuming only 1/2 of contracted vehicles are available for V2G at any one time, 3.2% of the light vehicle fleet would be on V2G contract for wind regulation.

Operating reserve needs for high-penetration wind include both spinning and non-spinning reserves, to cover all of interval 2 and part of interval 3 from Table 2. We find the most thorough analysis of these needs to be Milligan's (2001), which uses the Strbac and Kirschen (2000) model (hence, SR model). The SR model is used by the electric industry to allocate the cost of operating reserves to specific generating

[2] This section draws heavily from the analysis of Kempton and Tomic (2005b), and some passages in this section are directly drawn from the text of that article. This section is updated to better account for plug-in hybrids and offshore wind, whereas the analysis of photovoltaic electricity (PV) is omitted here.

plants within a mix of plants. In this model, the reserves are used to cover any shortfall between contracted generation and actual wind available—the storage needs are less stringent than those needed to guarantee constant baseload power from wind. Assuming dispersed wind generation and estimating some parameters not yet established for wind, Milligan uses the SR model to estimate reserves need, arriving at a maximum of 11% of wind capacity. (With "less reasonable assumptions" the maximum reserve need would be 20%.) Assuming as above 1/2 of US electric energy coming from wind generators with capacity of 700 GW, the 11% reserve need would be 77 GW. Milligan uses a three-hour rolling window, so we assume here that the maximum duration for the reserve requirement would be three hours.

From the SR operating reserve requirements (above), the number of EDVs to provide these operating reserves can be calculated. We calculate for an example of three electric-drive vehicle types; for each we assume that 27 km (16 mi) have been driven, and that the driver requires a "reserve" of an additional 32 km (20 miles) additional range; these assumptions limit the amount of battery charge or H_2 that can be drawn for V2G. Calculations use equations developed by Kempton and Tomic (2005a, 2005b)

For the Prodigy P200 prototype fuel cell vehicle described by Eq. (3) and Table 1 in Kempton & Tomic (2005a), power output per vehicle ($P_{vehicle}$) is 12 kW over 3 hours. At 12 kW per vehicle, the 77 GW reserve requirement could be met by 6.4 million fuel cell vehicles, or again assuming only 1/2 are available and adequately fueled when called, 12.8 million vehicles under V2G contract or 8% of the US fleet. For a battery vehicle with 27 kWh of storage, again using equations from Kempton & Tomic (2005a), we can draw 2.3 kW over a 3-hour reserve requirement. Thus, to meet 77 GW would require 33.5 million battery vehicles or, assuming 1/2 available, 38% of the fleet needed under V2G contract.

As an example plug-in hybrid, we use the DamlerChrysler Sprinter van, which has a 6 kW plug and 14.4 kWh of Li-ion storage. If the Sprinter PHEV provides V2G from the battery only and if we assume driving in a charge-depleting mode, the range assumptions above would exhaust the battery so it would not be able to provide any V2G power. On the other hand, we might assume that wind lulls would be predicted a day ahead and the PHEV would have been running in a "partial charge maintaining" mode. Given this, we might, for example, assume that there would be 60% of battery capacity available which, after inverter losses would be 7.8 kWh available for V2G. Given these assumptions, the PHEV would provide 2.6 kW over 3 hours; similarly assuming 1/2 available when needed, this would be met by 34% of the fleet under V2G contract.

The battery or plug-in hybrid vehicles would also be able to absorb the excess power that a 700 GW wind system would sometimes produce—assuming the same 33.5 million battery vehicles (38% of fleet) with 1/2 available and each absorbing 7.0 kWh, the fleet could absorb 235 GWh. With an average US load of 583 GW, 700 GW is 117 above average load, so the 235 GWh storage only absorbs two hours of full wind at average load, leading to "spilled power" as shown in Figure 2. In fact, there should be more power utilized than with a simple storage model, because some of the stored electricity is used for driving and also, as mentioned with the plug-in hybrid, wind prediction would allow charging to be deferred for vehicles with highly predictable driving patterns.

As a check on the SR model, an alternative approach is to estimate the size of storage needed to insure a given minimum firm capacity, as if there were no other generators in the electric markets. This mechanistic approach sizes storage dedicated

to wind, rather than using electricity markets (and existing generation) for operating reserves. Again we assume that to meet our benchmark of 1/2 of US wind generation, multiple widely distributed sites would be required. We find three analyses published on very large-scale, distributed wind.

Archer and Jacobson (2003, 2004) sum wind speeds over a year from a distributed set of eight US Midwest sites in an ellipse approximately 500 km by 400 km. The sum of wind power from eight sites approaches a normal distribution rather than a Rayleigh distribution, and never goes below 3 m/s for any four-hour block during the entire year. This study, and another one by DeCarolis and Keith (n.d.) with mid-continental wind sites separated by 1600 km, both suggest far less storage needed for widely distributed wind sites than for single or nearby sites. Finally, Geibel (2000) reports cross-correlations among wind at many sites in Europe, finding high correlations at nearby sites, dropping in an exponential decay function to near zero correlation at 1500 km, with a lot of dispersion around the fitted curve. However, none of the three reports offer the type of data we need to calculate storage requirements.

We here use an unpublished data set from Archer, based on the eight Midwestern US sites. This data is disaggregated to hourly and adds calculation of energy at each site, based on actual wind turbine performance (a GE 1.5 MW turbine at 80m hub height), summed to yield hourly total energy for all sites combined. These data allow us to calculate directly the amount of storage needed for a distributed wind resource, which yields a transparent calculation, and does not require the SR model's assumption of electricity markets using existing generators. We assume storage would be used to maintain a 20% firm capacity. (This level would be set by the wind seller; higher firm capacity values require more storage but increase revenue and make wind viable for a larger fraction of the generation mix.) In the 6916 hours of valid data, we find 1109 hours in which the power was under 20% of rated capacity. Grouping contiguous hours, we find 342 low-power events and compute the shortage in hours and in total MWh for each event. Figure 3 shows the durations of events under the contract amount of 20%. The vast majority are 3 hours or less, as shown in Fig. 3. Just over 150 of the total 342 events were 1 hour or less. The majority of need for storage could be met by small storage. Only twice during the year did a shortfall occur for over 16 hours, and never for over 24.

Figure 4 shows the MWh shortfall for each event. Sixty percent of these events require only 3-10% of capacity (e.g. MSBR of 0.03 to 0.1 h), easily handled by V2G. Storage need is determined by the worst cases: In Fig. 4, the worst cases are the rightmost cluster of five events with MWh shortfalls of about 170% of the MW wind turbine capacity. These five range from 14 to 22 hours duration. In the solar energy backup metric, 170% is 1.7 hours MBSR[3].

[3] We define "valid data" as having wind data from at least 7 of the 8 weather stations. The number of shortfalls is exaggerated by missing data. When we examine only hours with all eight weather stations available, we find only 122 shortfall events rather than 342, and only one of the above-mentioned five largest shortfalls. Since one of the largest events remains, correction for missing weather data would substantially reduce the number of events but not significantly change the largest event, from which we calculate storage needs.

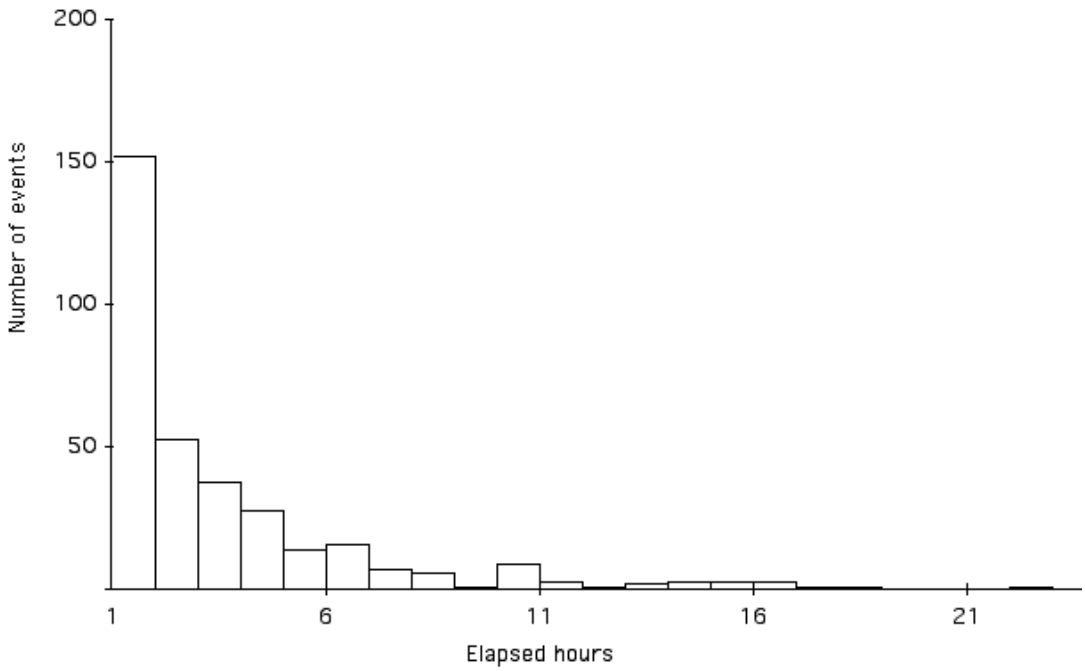

Figure 3. Durations of the 342 shortfall events during one year.

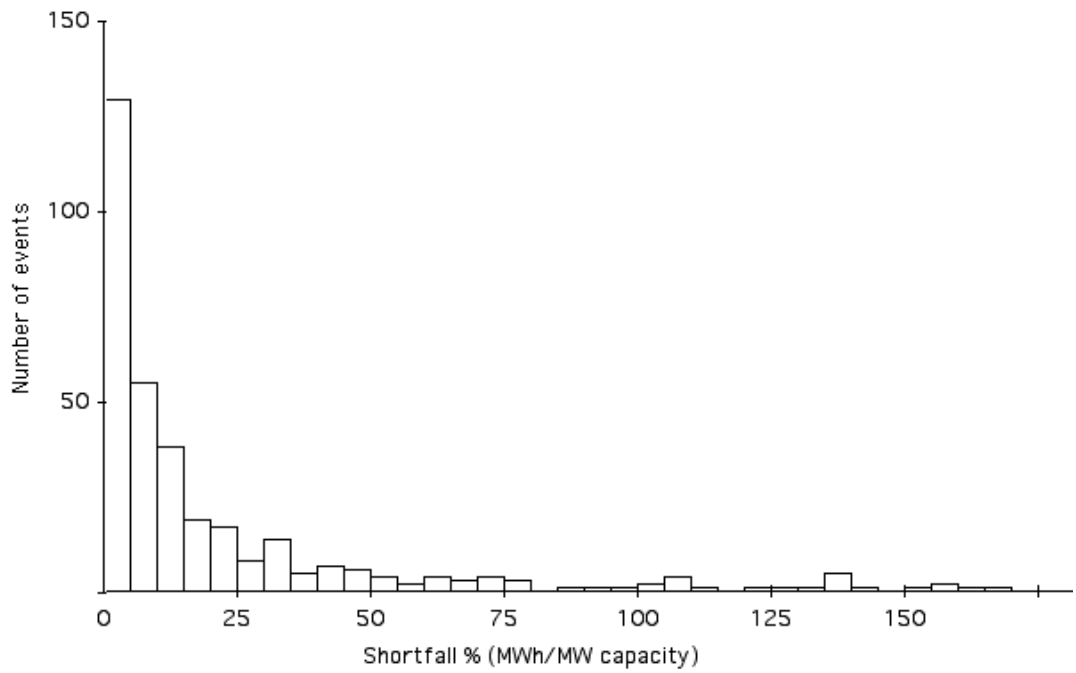

Fig. 4. Shortfall of energy as percent of wind capacity, in 342 events during a year. Calculated as 100 * shortfall (MWh) / peak output (MW). We assume a contract for firm power at 20% of the wind turbines' rated maximum capacity. Based on Archer data on 8 connected wind sites, aggregated to hourly.

Taking our scenario of 700 GW wind capacity, the largest shortfall,170% is 1,190 GWh storage needed. Using the numerator of Eq. (3) in Kempton & Tomic (2005a), the example fuel cell vehicle has available energy of 36 kWh from stored

hydrogen and the plug-in hybrid 7.8 kWh from battery only. We assume that over a 14 to 22 hour wind shortfall period, most vehicles would be driven, so the plug-in hybrid would recharge from fuel as part of normal driving, or the fuel cell vehicle could refill with H_2. Thus, we assume that 3/4 of the vehicles under V2G contract would be available over the 14-22 hour shortfall period (rather than 50% assumed in prior examples). So, the storage need for 1,190 GWh, would require 33 million fuel cell vehicles on-line (44 million on contract), or 152 million plug-in hybrids (203 million on contract). In a fleet of 176,000,000 vehicles, this becomes a need for V2G contracts with either 25% of the fleet of fuel cell vehicles or an impossible 116% fleet of plug-in hybrids. (If the plug-in hybrid were allowed to run its motor- generator when parked during these long backup needs, the number of vehicles needed would be small, even less than for fuel cell vehicles, because of the greater energy content of liquid fuel storage.) The battery vehicle is not suitable for these long storage intervals.

Although these illustrative calculations give the fleet percentage needed, in each case for only a single vehicle type, our analysis above and in Kempton & Tomic (2005a) suggest that optimum vehicle support for the pattern of shortfall events in Fig. 3 would be: 1) storage from battery or hybrid in battery mode for the most frequent and low-energy shortfalls on the left of Figure 3, and 2) backup from the fuel cell or hybrid in motor-generator mode, for the less frequent high energy shortfalls on the right of Fig. 3.

Table 3. V2G required to support large-scale wind as baseload, assuming it is ½ electrical energy in US, peak capacity 700 GW; see text.

Support criterion	Support quantity	Veh. avail-ability	Fleet % needed, vehicle type
Regulation	42 GW	1/2	3.2% battery
Operating reserves (SR)	77 GW	1/2	8% fuel cell, or 38% battery, or 34% plug-in hybrid
Firm capacity at 20% (dedicated storage)	1190 GWh	3/4	23% fuel cell

The results are summarized in Table 3. Note that the "firm capacity" calculation is more stringent in requiring dedicated storage, whereas the operating reserves calculation assumes taking advantage of existing generation and existing markets.

This analysis, the above calculations summarized in Table 3, and indeed our previous Table 2, all suggest that V2G could play a role as storage for intermittent wind, even when wind becomes half (or more) of total electrical generation. V2G could be the critical missing piece of the system that enables intermittent wind energy to provide much of society's energy needs, without large storage costs, while keeping the electric grid stable and reliable. In addition to the support of renewable energy, there are environmental and geopolitical benefits from operating the light vehicle fleet from domestic renewable energy—an understatement we do not quantitatively analyze here.

Conclusions

The light vehicle fleet represents a large energy storage resource. Because it will be changed to new energy technologies at the same time that wind power undergoes rapid expansion, there is an opportunity for synergies between the storage of the fleet and the intermittent nature of the wind resource. As we have shown in this article, multiple types of electric drive vehicles can pay valuable roles as backup and/or storage for wind power, eventually making very large scale wind integration more stable and more economical. Because offshore wind resources are very large and are typically close to urban areas, V2G may be especially suited as storage and backup for offshore wind.

References Cited

Archer, Cristina L., and Mark Z. Jacobson (2005), Evaluation of global wind power, J. Geophys. Res., 110, D12110, doi:10.1029/2004JD005462.

Archer, Cristina L. and Mark Z. Jacobson, Spatial and temporal distributions of U.S. winds and wind power at 80 m derived from measurements, J. Geophys. Res. 108 (D9) (2003) 4289. (See correction, Archer and Jacobson 2004.)

Archer, Cristina L. and Mark Z. Jacobson, 2004, Corrections to Spatial and temporal distributions of U.S. winds and wind power at 80 m derived from measurements. Manuscript accepted (August 2004) for publication by J. Geophys. Res.-Atmospheres. Also available from authors, Dept Civil Engr., Stanford University (2004). (This is a correction to Archer and Jacobson 2003.)

Archer, Cristina L., and Mark Z. Jacobson (2005), Evaluation of global wind power, J. Geophys. Res., 110, D12110, doi:10.1029/2004JD005462.

Bossel, U., 2004, Hydrogen: Why its future in a sustainable energy economy will be bleak, not bright. Ren. Energy World 7 (2004) 155.

Brooks, Alec, 2002. "Vehicle-to-Grid Demonstration Project: Grid Regulation Ancillary Service with a Battery Electric Vehicle" Report, AC Propulsion, December 2002. Available at: http://www.udel.edu/V2G

Cavallo, A., 1995, High-Capacity Factor Wind Energy Systems. J. Solar Energy Eng. 117 (1995) 137.

J. F. DeCarolis, D.W. Keith, n.d. The Economics of Large-Scale Wind Power in a Carbon Constrained World. Energy Policy, accepted for publication and available online, July 2004.

Denholm, Paul, Gerald Kulcinsis, and Tracey Holloway, 2005, "Emissions and Energy Efficiency Assessment of Baseload Wind Energy Systems." Environmental Science and Technology 39: 1903-1911. doi: 10.1021/es049946p

EIA (Energy Information Administration, US), 2001, Electric Power Annual 2000, Vol I. DOE/DIA-0348(2000)/.1, Energy Information Agency: Washington DC.

Firestone, Jeremy, W. Kempton, A. Krueger, and C.E. Loper, "Regulating Offshore Wind Power and Aquaculture: Messages from Land and Sea (proof sheets), *Cornell Journal of Law and Public Policy*, 14 (1): 71-111.

Gage, Thomas B., 2003. "Final Report Development and Evaluation of a Plug-in HEV with Vehicle-to-Grid Power Flow" Report, AC Propulsion, December 2003. Available at: http://www.udel.edu/V2G

Geibel, Gregor, 2000, "On the Benefits of Distributed Generation of Wind Energy in Europe". Vom Fachbereich Physik der Carl von Ossietzky, Universität Oldenburg (PhD Dissertation). Available as dissertation, or at: http://www.drgiebel.de/thesis.htm

Hirst, E., J. Hild, Integrating Large Amounts of Wind Energy with a Small Electric-Power System, Manuscript, available as of October 2004 at http://www.ehirst.com/publications.html. (Manuscript, April 2004)

Hudson, R., R. Kirby, Y. Wan, 2001, Regulation Requirements for Wind Generation Facilities. Proceedings of the Windpower 2001 Conference, Washington, DC: American Wind Energy Association.

Kempton, W., J. Firestone, J. Lilley, T. Rouleau and P. Whitaker, 2005, The Offshore Wind Power Debate: Views from Cape Cod. *Coastal Management Journal* 33 (2): 119-149.

Kempton, Willett and Toru Kubo, Electric-drive vehicles for peak power in Japan, Energy Policy, Volume 28, Issue 1, 1 January 2000, Pages 9-18.

Kempton, W. and Steven Letendre. 1997. "Electric Vehicles as a New Source of Power for Electric Utilities" *Transportation Research* 2(3): 157-175.

Kempton, W. and J. Tomic. 2005a. "Vehicle to Grid Fundamentals: Calculating Capacity and Net Revenue" *J. Power Sources* Volume 144, Issue 1, 1 June 2005, Pages 268-279. doi:10.1016/j.jpowsour.2004.12.025.

Kempton, W. and J. Tomic. 2005b. "Vehicle to Grid Implementation: from stabilizing the grid to supporting large-scale renewable energy". *J. Power Sources* Volume 144, Issue 1, 1 June 2005, Pages 280-294. doi:10.1016/j.jpowsour.2004.12.022.

Kempton, W., J. Tomic, S. Letendre, A. Brooks & T. Lipman. 2001. Vehicle-to-Grid Power: Battery, Hybrid, and Fuel Cell Vehicles as Resources for Distributed Electric Power in California. UCD-ITS-RR-01-03. Available at: http://www.udel.edu/V2G

J.F. Manwell, J.G. McGowan, A.L. Rogers, *Wind Energy Explained: Theory, Design and Application*, John Wiley & Sons Ltd. West Sussex, Britain (2002). (Reprinted with corrections Aug 2003).

Milligan, M.S., 2001, A chronological reliability model to assess operating reserve allocation to wind power plants, Presented at the 2001 European Wind Energy Conference (Copenhagen, Denmark July 2–6, 2001). Document # NREL/CP-500-30490. Available Oct 2004 at http://www.osti.gov/bridge.

Strbac, G., D. Kirschen, Who should pay for Reserve? Electricity J. 13 (2000) 32.

Susan M. Schoenung, James M. Eyer, Joseph J. Iannucci, and Susan A. Horgan (1996), Energy Storage for a Competitive Power Market, Annu. Rev. Energy Environ. 21:347-70.

Schainker, S.B. (1990), Strategic Benefits of Energy Storage. Proc. Electr. Util. Bus. Environ. Conf. Exhib., Denver. Greenwood Village, CO: Electr. Util Consult.

Tomic, Jasna, and W. Kempton, n.d., "Using Fleets of Electric-drive Vehicles for Grid Support", manuscript submitted for publication, 2005. Available from authors.

For additional information on V2G, see http://www.udel.edu/V2G/, for more information on the University of Delaware offshore wind program, see http://www.ocean.udel.edu/windpower/