

*The world's wind resources are huge. But as wind becomes a larger fraction of electricity generation, grid integration must be resolved, particularly to smooth fluctuations in wind power output. Adding energy storage or back-up has been proposed as a solution, but dedicated storage or back-up adds capital cost to wind power. This article proposes vehicle-to-grid power (V2G) as a storage resource for large-scale wind power.*

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## Electric Vehicles with V2G

### Storage for Large-Scale Wind Power

From an electric utility perspective, wind alone is an intermittent electrical generator, tolerable in small quantities but increasingly difficult to manage as it becomes a larger fraction of the mix of generators. This problem can be addressed with storage or back-up power. Here we propose an innovative approach to creating large-scale, inexpensive storage for wind power.

As electric vehicles (such as battery and plug-in hybrid vehicles) become a larger fraction of the light vehicle fleet, vehicle-to-grid power (V2G) offers the opportunity to use the distributed electrical storage inherent in these vehicles. Such vehicles will reduce the petroleum needs of the light vehicle fleet, and tapping their storage via V2G could simultaneously stabilise wind generation, allowing wind to become a larger fraction of the generation mix.

#### Concepts of Storage and Back-up for Wind Power

Storage and back-up of wind power are distinguished as follows. Back-up 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

energy when wind power is excessive.

Other than levelling wind output, electrical storage also provides additional benefits. As described by Schoenung et al. (1996, p. 358), 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 stor-

age to optimise several important aspects of utility electricity 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 the Electric Power Research Institute (EPRI) indicates that energy storage can reduce uncertainty in providing energy supply such that the overall value of storage on a per-megawatt basis is 40% greater than other generating alternatives (also see Schoenung

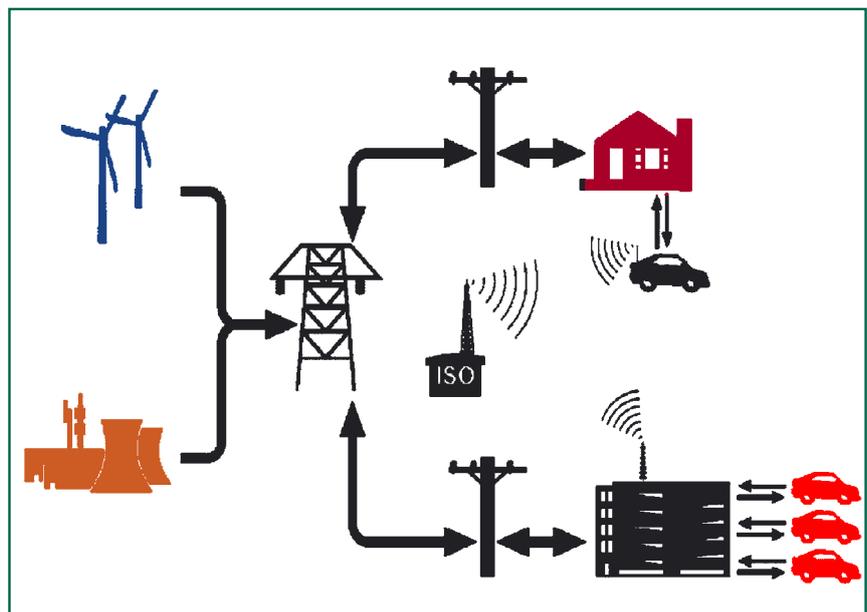


Figure 1. Concept of V2G illustrated

et al., 1996). In liberalised electric power markets, many of these benefits correspond to electric markets. The existence of these markets means that V2G power can be sold today, regardless of whether or not there is a wind integration need yet.

The two approaches of storage and back-up can be combined. For example, if a smaller storage is provided, slow ramp-up back-up can be provided to fill in the end of extended wind gaps lulls. In this case, the storage provides a long lead time prior to need for the back-up, thus allowing use of slow ramping back-up generators.

Existing fossil fuel generators, especially fast-response ones like natural gas and hydroelectricity, can be used for wind back-up. New large-scale storage technologies such as pumped hydro, large battery banks and compressed air energy storage (CAES) can be built for wind electric storage. But, before we resign ourselves to the costs of building storage or back-up dedicated for intermittent wind power, we should first ask, 'Is there any unused storage already in the system?'. Surprisingly, the answer to that question is, 'Yes, there is, quite a bit'. The existing storage, as

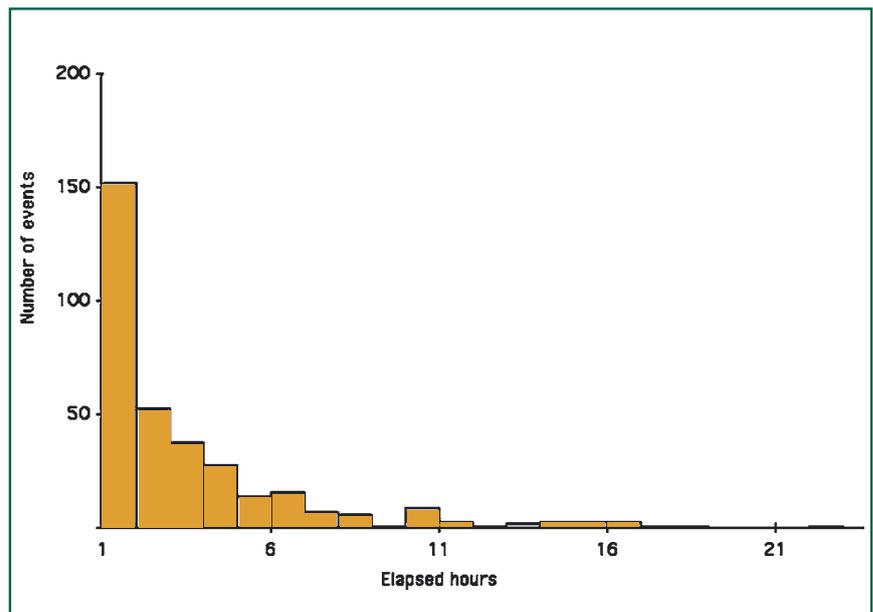


Figure 2. Durations of the 342 shortfall events during one year, based on wind data and assuming that power is combined from eight dispersed wind sites

for back-up 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 hybrid electric vehicles (PHEV), but could be added for fuel cell vehicles. The electric grid operator must control specific times of discharge or charge. The concept is illustrated in Figure 1.

Kempton, Tomic' Brooks, Gage, Cocconi and colleagues have

nise to the grid, for controls, and for protection from energising a dead line. A power controller can now be purchased with V2G capability, which has a 20kW line connection at 208/240V AC. The incremental capital cost to add V2G is approximately € 400 per vehicle, which is less costly than other storage options on a per kilowatt capital cost basis (€ 22/kW or US\$ 33/kW).

Operationally, private light vehicles are in use for 1 hour per day and parked for 23 hours per day (in the US; time driving is less in other OECD countries, e.g. Kempton et al. 2001). Therefore, depending on parking locations, vehicles could potentially be connected to the electric grid for most of the day. 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).

For wind power support, V2G back-up can be provided by fuelled vehicles, such as fuel cell vehicles and hybrids running motor-generators. Storage can be provided by the battery vehicle and the plug-in hybrid running V2G from its battery. Could hydrogen-pow-

### *Is there any unused storage already in the system?*

first pointed out by Kempton and Letendre in 1997, is in the light vehicle fleet. This currently mostly uses liquid fuel that is combusted to turn a shaft, which is of little value to wind operators or electric utilities. However, most of the emerging electric drive vehicle types (battery, hybrid, and/or fuel cell vehicles) will produce alternating current onboard.

### **V2G as Back-up and Storage**

How are electric vehicles used

conducted extensive analyses of the engineering and economics of this configuration (see 'Further Reading' and 'Web Resources on V2G and Wind'). Their findings demonstrate that a high-power connection is practical (10–20kW), line frequency and interconnect standards can be met, and the economics are favourable (Kempton et al. 2001; Gage 2003). Capital costs of V2G are incurred by adding circuitry to synchro-

Vehicle type	Wind function		Electric markets		
	Back-up	Storage	Regulation	Spinning reserves	Non-spinning reserves
Battery		++	++	++	
Plug-in hybrid	++	+	+	++	++
Fuel cell	++				++

Table 1. Suitability of different vehicle types for wind power storage versus back-up, and for differing electric markets. ++ very suitable, + suitable, (blank) not suitable

ered fuel cell vehicles be considered electrical storage, if the hydrogen is produced on site 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) 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 back-up is laid out in Table 1. The table also illustrates another

and providing 15kW to the grid. For example, in the first row, Denmark, we see that the country has about 1.9 million cars. If each were producing 15kW, that would be 29GW. The fourth column is the average electrical load of Denmark, 3.6GW, and the fifth column gives the ratio of V2G potential to average electrical load. Thus a Danish V2G fleet at 15kW would produce 805%, or about 8 times the average load. Of course, not all vehicles would be electrified, have V2G, and be plugged in and charged at the

*The V2G power potential is very large, but not unlimited*

difference, that some vehicles are better for shorter-term electric markets, like regulation and spinning reserves, while others are better for longer-term markets, like non-spinning reserves.

moment needed. But with a factor of 8 more than needed, V2G could pick up the entire electrical load if, for example, only a quarter of the light vehicle fleet had V2G and only a half of those vehicles

### National Comparisons of V2G Potential

Given the type of V2G vehicles that have been built, and assuming a maximum electrical plug connection of 15kW (220V at 70A), 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 second column of Table 2 gives the size of the light vehicle fleet in each country, and the third column calculates the power that would be produced if each of these vehicles were plugged in

Country	Number of passenger vehicles	V2G @ 15kW from all vehicles (GW)	Average national load (GW)	All vehicles @ 15KW/ average load (%)
Denmark	1.900.370	29	4	805
France	29.218.210	438	50	885
Germany	44.652.517	670	58	1.149
Ireland	1.470.644	22	2,6	846
Italy	33.819.390	507	34	1.473
Netherlands	6.865.832	103	12	888
Portugal	5.807.664	87	5	1.740
Spain	18.714.180	281	26	1.068
Sweden	4.050.273	61	15	407
UK	28.447.908	427	40	1.081
USA	191.000.000	2.865	417	686

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

were plugged in and available when needed.

It should be apparent from the quick calculations in Table 2 that the V2G power potential is very large, but not unlimited. This is only a power calculation, and does not consider the energy storage and the amount of time power could be drawn relative to both wind lulls and driving needs. We next calculate more precisely the amount of wind power that would be enabled by a large V2G fleet.

### How Much V2G is Needed to Integrate Large-Scale Wind Power?

We calculate the storage needed for wind power using hourly wind speed data from eight dispersed US land sites. The wind speeds are converted to electrical energy at each site, based on actual wind turbine performance (a GE 1.5MW turbine at 80m hub height), summed across the eight sites to yield hourly total electricity. As an example here, we assume that storage is used to maintain a 20% firm capacity, that is, a firm capacity requirement roughly two-thirds of an average 33% wind capacity factor. (This level would be set by the power contract for wind; higher firm capacity values require more storage but increase revenue and make wind viable

for a larger fraction of the generation mix.) In the 6,916 hours of valid data in the study year, we find 1,109 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 megawatt-hours for each event. Figure 2 shows that the durations of events under the contract amount of 20%. The vast majority are 3 hours or less, as shown in Figure 2. 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 that would be called frequently – an ideal application for V2G. Only twice during the year did a shortfall occur for over 16 hours, and never for over 24.

These calculations suggest that V2G would serve the majority of need for integrating wind into the electrical system. This calculation is described in more detail in Kempton and Tomić (2005b), and is currently being modelled more fully by Henrik Lund and Willett Kempton for the Danish electrical system, and by Walter Short and colleagues for the US electrical system.

The cited analysis, along with the values in Table 2, suggest that V2G could provide storage to level out the fluctuations of wind power, even when wind becomes half (or more) of total electrical generation. V2G could be the critical missing piece of an integrated electrical-transportation 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, fuelling the vehicle fleet from domestic renewable energy has environmental, security and geopolitical benefits – an understatement we do not analyse quantitatively here.

## Conclusions

The light vehicle fleet represents a large energy storage resource. Fortunately, it is changing to new drive systems during the same interval that wind power undergoes rapid expansion. Therefore, 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, V2G enables multiple types of electric drive vehicles to play valuable roles as back-up and/or storage for wind power, eventually making very large scale wind integration more stable and more economical.

## Further Reading

Gage, T.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>

Kempton, W. and Letendre, S., 1997, Electric vehicles as a new source of power for electric utilities, *Transportation Research* 2(3), pp. 157–175

Kempton, W. and Tomić, J., 2005a, Vehicle to grid fundamentals: calculating capacity and net revenue, *Journal of Power Sources*, 144(1), 1 June 2005, pp. 268–279, doi:10.1016/j.jpowsour.2004.12.025

Kempton, W. and Tomić, J., 2005b, Vehicle to grid implementation: from stabilizing the grid to supporting large-scale renewable energy, *Journal of Power Sources* 144(1), 1 June 2005, pp. 280–294, doi:10.1016/j.jpowsour.2004.12.022

Kempton, W., Tomić, J., Letendre, S., Brooks, A. and Lipman, T., 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>

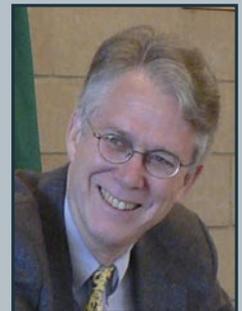
Schoenung, S.M., Eyer, J.M., Iannucci, J.J. and Horgan, S.A., 1996, Energy storage for a competitive power market, *Annual Review of Energy and the Environment* 21, pp. 347–370

## Web Resources on V2G & Wind

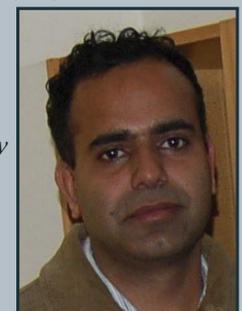
Overview, technical articles and reports on V2G: <http://www.udel.edu/V2G/> A tested V2G system (see AC-150 specifications): <http://www.acpropulsion.com> Offshore wind power and V2G: <http://www.ocean.udel.edu/windpower/> ■

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