Using fleets of electric vehicles electric power grid support

The growth of intermittent renewable energy sources such as solar and wind power, as well as heat-driven microgeneration (building-based CHP), requires utilities to find additional grid-coupled energy storage and regulation capacity. Remotely managing the (dis-)charge behaviour of future (plug-in hybrid-) electric vehicles - (PH)EVs - may serve as a means to realise this. The concept of deploying (PH)EVs to stabilise the electric power grid is generally referred to as ‘Vehicle-to-Grid’ (V2G).

This document serves as a primer on the topic of V2G for policy makers, regulators and other decision makers, and contains references to materials for more research into the subject.

The Vehicle-to-Grid concept

The concept of ‘Vehicle-to-Grid’ (V2G) was first proposed in 1997 by professor Willet Kempton of the University of Delaware in his article “Electric vehicles as a new power source for electric utilities” (see reference list).
What is V2G?

(PH)EVs have a battery pack (energy storage device) and a charger. The charger can be bidirectional; able to deliver power back to the grid from the vehicle’s battery as well as charge the battery. Typically, the battery recharge time is only a few hours. Since most vehicles are generally in use just a couple of hours per day, there is a flexibility to the timing and power profile of how and when vehicles are recharged, or even discharged into the grid.

Kempton’s concept of V2G is based on such vehicles with remotely controlled, bidirectional chargers providing services to the electric power grid. The services that these vehicles provide to the grid have a value that may result in payments back to vehicle drivers, resulting in lower vehicle operating costs.

Grid services: Regulation / balancing / ancillary services

Electric power grids require fast-response units to provide or absorb power in case of unexpected power fluctuations (e.g. outage of a power plant, or sudden high wind power generation) and for balancing, i.e. the bridging the gap between altering demand or supply and the response of the generally slow large generation units.

Renewable energy sources such as solar and wind power, as well as heat-driven microgeneration (building-based CHP) increase the demand for reserves and regulation due to their intermittent nature.

The actual definitions may differ per country or region, but this reserve/balancing capacity is generally referred to as ‘ancillary services’.

- (Spinning) reserves

Spinning reserves represent generating capacity that is up and running, and synchronized with the electricity grid. Generators of spinning reserves contribute to grid stability, helping to arrest the decay of system frequency when there is a sudden loss of another generator. Providers of spinning reserves need to be able to ramp up output rapidly; within seconds to minutes.

Spinning reserves are unbundled and priced as a separate service—for example; a generator with spare capacity may market this to the grid operator as spinning reserves. These will then operate at less that 100% of their capacity (mostly 94%), so that there is regulating capacity left. Spinning reserved are usually deployed in blocs of less than 15 minutes.
Any capacity that is immediately available could be qualified as a ‘spinning reserve’ even if the device is not literally spinning. Cars that can immediately dispatch power into the grid could thus serve as spinning reserve.

- **Balancing services**

  Regulation / balancing services are necessary to bridge the mismatch between demand and supply (the ‘area control error’ or ACE), which occurs due to the inherent slowness of large generating units; these can never exactly follow the demand. Regulation services eliminate the area control error and are usually required only for seconds to minutes. Depending on system needs, providers of regulation services may need to increase (this is called ‘Regulation Up’) or reduce (this is called ‘Regulation Down’) their output. In many power markets, regulation services are priced separately from power generation, based on availability and dispatch.

  ![Diagram](image)

  In some markets, providers of regulation services have to be able to provide both regulation up and regulation down. In other markets, these two are unbundled, and may be sold separately.

  **New development: Load-only balancing services**

  Presently, grid ancillary services in most countries are not provided by loads. However, loads appear to be capable of providing grid regulation just as effectively as generation plants which usually supply this service. Grid regulation provided by ‘loads only’
(demand response management; DRM) is increasingly getting attention by researchers and TSOs. DRM can result in a ‘virtual power feed-in’ by reducing the load on the grid.

**Daily peak power** is usually also sold a a service. If fleets of electric vehicles would deliver daily peak power, it is the most demanding scenario from a battery and user point of view: It requires much more energy from the vehicle than grid balancing services and spinning reserves (i.e. longer charge/discharge periods; in the order of hours). This causes more wear on the batteries and makes it less certain that a car has sufficient range if a user suddenly needs it.

Therefore (PH)EVs are most suitable for grid balancing; regulation up and regulation down. After that, they could act as ‘spinning’ reserve, only to be deployed with a low frequency.

Daily peak power operation is the least viable way of deploying V2G (PH)EVs, due to battery- and vehicle usage constraints.

1. **Grid balancing services (regulation up and regulation down)** are usually required only for seconds to minutes and thus only ‘shallow-cycle’ the battery. In addition, the battery can be kept relatively full, which is beneficial for the owner/user of the vehicle with regard to range.

2. **Spinning reserves (for emergencies)** are only deployed occasionally and therefore impact battery life relatively little.

**V2G is a continuum**

The original ‘Kempton’ V2G concept comprises bi-directionally capable chargers, allowing a vehicle to both feed power into the grid as well as taking it out. Increasingly, the V2G concept is considered a continuum, ranging from unidirectionally (i.e. load-only) grid-coupled vehicles of which the charger can be turned off/on remotely, to ‘full’ V2G with bi-directionally capable chargers.

If the TSO can control the timing and power level of vehicle charging, the load-only option seems attractive; it adds the least additional costs to the vehicle, and does not affect battery life. Grid regulation provided by ‘loads only’ (demand response management; DRM) is increasingly getting attention from researchers and TSOs.
Example of load-only regulation:

100,000 EVs with 2kW chargers charging at 1kW, battery state-of-charge is 50%:

- **Regulation up:** reduce charging speed; max 100,000 x 1kW = 100MW available
  This has the same effect as 50,000 EVs discharging their batteries into the grid with 2kW

- **Regulation down:** increase charging speed; max 100,000 x 1kW = 100MW available

It can thus be said that V2G is a continuum, ranging from simple remote ‘on/off’ management of the charger, to adjustable high-power electricity feed-in during peak demand periods.

**Environmental and system benefits**

Even though providing ancillary services (spinning reserves and balancing services) does not serve to store large quantities of electricity on a daily basis, it does have strong environmental and system advantages:

- It could allow more large generating units to operate at 100% capacity instead of 94% (spinning reserve margin), which increases the efficiency of these units;

- It allows for a higher share of intermittent energy sources (wind, solar), since there is more regulating capacity to even out wind fluctuations and allows for a longer ramp-up time for larger generating units.
Aggregators

In order to make V2G work properly, service providers (aggregators) will be required to organise MW-size ‘blocks’ of regulation/reserve/peak power. These service providers need to be able to communicate with the vehicles to obtain vehicle location, battery state-of-charge, owner preferences, and to transmit ‘charge’ or ‘dispatch’ signals.

State of the Technology

- **Power electronics**: Two US companies offer bi-directionally capable electric drive systems: HybridsPlus and AC Propulsion. Demonstrations that do not use AC Propulsion or HybridsPlus equipment generally use solar DC-AC inverters. AC Propulsion and HybridsPlus state that in series production, a bi-directional charger does not have to be significantly more expensive than a ‘normal’ charger.

  Depending on battery type and the % of full capacity at which the charge/discharge cycle takes place, the bidirectional efficiency of a V2G system is between 45% and 85%.

- **Vehicle batteries I**: In the next 3-5 years, there will be no batteries available for OEM-scale (i.e. >100,000 units) production of (PH)EVs, even though the batteries to build a usable (PH)EV do exist. However, large-scale production of batteries larger than 10-15kWh for the right price and with sufficient quality is still a challenge; (PH)EVs will thus remain a niche market at least until 2013/2013.

- **Vehicle batteries II**: Even though NiMH and Zebra batteries currently have the largest market share for (H)EV batteries, experts agree that the future of (PH)EV batteries is Lithium-based. The most probable candidates for large-scale production of (P)(H)EV batteries will either be based on Lithium-titanate or on Lithium-iron-phosphate:

  **Lithium-iron-phosphate (LiFePO4-cathode) batteries**
  High energy density, reasonable cycle life (±2,000x) \(\rightarrow\) well-suited for EVs
  \(\rightarrow\) due to the relatively limited cycle life, this battery type is less suitable for feeding power back into the grid, although ‘full’ V2G operation may still be an economically viable use of this battery type
Lithium-titanate (Li4Ti5O12-anode) batteries
Lower energy density, high power, high cycle life (>10,000x) → well suited for HEVs and larger EVs that require fast-charging (taxi’s, buses)
→ due to the high cycle life and high power capability, this battery is very suitable for ‘full’ V2G operation

- **Smart meters:** Metering of the V2G contribution to the grid of individual vehicles can be done with residential ‘smart’ meters, which are widely commercially available. Both in the US and in the EU, taskforces/working groups are working on standards for smart meters (US: UtilityAMI/OpenHAN, EU: NTA 8130).

Another option is to use an on-board metering device; this seems to make more sense in the case that the vehicle is controlled by an aggregator.

Either way, a solution needs to be found for the situation in which a bidirectional V2G-vehicle is not connected to the residential wall socket of the vehicle owner, but for example to the socket at the office.

- **Communication:** Several ‘smart grid’ companies in the US are active in providing communication solutions between V2G-vehicles and TSOs/aggregators; examples are V2Green and GridPoint.

- **Standards for charge/discharge communication:** In the US, The National Electric Infrastructure Working Council (IWC, organised by EPRI) is working with the automotive industry to define a communications standard, enabling EVs to communicate to their charging infrastructure. The IWC is working closely with the SAE J1772 (EV charging standard) committee.

**Description of a V2G system**
A V2G-capable (plug-in hybrid) electric vehicle is equipped with an on-board electrical power source and a (bi-directional) connection to the public power grid. Furthermore there is a way to control the power that goes to/from the vehicle. For the purpose of this overview, only electric and plug-in hybrid electric vehicles are taken into account, although fuel-cell electric vehicles can also be made V2G-capable.
V2G-relevant vehicle components

- **Battery**
  PHEVs have advanced batteries with a storage capacity of 4 to 15kWh, giving the vehicle an electric-only range of 15-80km. EVs generally have 15 to 50kWh on board, for a range of 80-300km.

  (PH)EV batteries should be able to provide a power of at least 30kW, to ensure convenient acceleration. The DC voltage of PH(EV) batteries is generally between 180V and 400V DC.

- **Battery management system (BMS)**
  Since individual battery cells have a voltage ranging from 1.2V to 3.6V, (PH)EV batteries are built from ±hundred to several thousands of battery cells. Such a multi-cell, high-energy battery pack requires complicated electronics and software to manage voltage, current levels and temperatures for each individual (module of) cells. This system is called the battery management system (BMS). The BMS also keeps track of the state-of-charge (SOC) of the battery, and controls the maximum power level of the charger and the maximum regenerative breaking level.

- **Battery charger (AC-DC) & inverter (DC-AC)**
  (PH)EV chargers have an output voltage of 180-400 Volt DC. If they are rated for a standard 220V AC socket, their maximum (dis-)charge power in Europe is generally ±3.5kW. In the US, the residential socket output is 110V, and maximum power output
limited to ±1.5kW. If a two-phase AC outlet is used, a much higher charge power can be drawn (15-20kW is the current state-of-the art). In many European countries, there is a 2-phase 380V connection inherently present in every home, since the electricity system brings a 3-phase cable (3 x 220V) to every household. A 380V socket can then easily be added to a residential or small business connection.

Most V2G research goes from the assumption that future (PH)EVs will have a charger with a (dis-)charge power level of 10-20kW, and that there will thus be dedicated EV charging connections installed in the house of (PH)EV owners.

The battery management system controls the maximum charge level of the charger, which is usually connected to the BMS via a CAN-interface.

In order to let the battery deliver power back to the grid, either the charger needs to be bi-directional, or a separate DC-AC inverter is required.

- **Controller, GPS & electricity meter**

To regulate the power taken from or fed into the grid by the vehicle, a remotely controlled regulation device is required. The signal that controls the regulation device can be provided in the following ways:

  - via the cellular phone network
  - via a radio signal
  - via the ‘Internet’ (last part WLAN connection)
  - via a ‘smart meter’ network (last part wirelessly, first part Internet or cellular phone network)
  - via the power grid (TSO signals)

Ideally, a GPS device keeps track of where the vehicle is and an on-board electricity meter measures in- and outflow of electricity.

- **Outside vehicle: (Smart) meter**

In a less advanced V2G scenario, it is not the on-board meter that measures electricity consumed and generated by the vehicle, but a (smart) residential electricity meter.
V2G R&D Worldwide

Government-funded R&D groups

Vehicle-to-Grid research and development started in the United States in 1997 and is still predominantly a US-led research field. Also, most real-world demonstrations take place—or are planned—in the US.

In Europe, some activity is emerging, mainly in Northern Europe; the field has lot of interest from especially Denmark. Furthermore, there is some R&D activity in the Netherlands, the UK and Austria. In Asia, the topic is not an area of significant R&D activity.

The following organisations that are active in V2G research have been identified (see also the publications/presentations list):

United States

- University of Delaware, College of Marine and Earth Studies (Professor Kempton’s group)
  Development of fundamental equations for power capacity and economics, customer interface, appropriate markets, cost factors (wear, losses, etc.)

- Institute of Transportation Studies, University of California at Davis

- Green Mountain College (Steven Letendre’s group)

- The Electric Power Research Institute (EPRI), (Mark Duvall’s group)

- California Air Resources Board (CARB)

- AC Propulsion
  Develops, produces, and markets full drive system with V2G capability. AC Propulsion has been running on a V2G vehicle on ISO regulation signal since 2001, and has produced several reports and scientific publications on the topic.

- V2Green
  US ‘smart grid’ start-up company providing real-time communication between plug-in electric vehicles and the power grid for V2G purposes.
- **HybridsPlus**
  HEV to PHEV conversion engineering company that has developed a bidirectional charger (called the ‘Inverger’).

- **Various Department of Energy (DOE) Laboratories**

- **National Renewable Energy Laboratory**

- **Battelle Laboratory**

- **Argonne Laboratory**

**Europe**

**Denmark**

The Danish Government has made the V2G subject area a priority, due the high penetration of wind power in this country:

- **Risø National Laboratory/Technical University of Denmark, Wind Energy Department**
  This department does research into load management and energy storage to stabilise the grid.

- **Aalborg University, Denmark, professor Henrik Lund (Department of Development and Planning).**
  Research the into integration of wind power into the electric power grid. Several publications on the role of electric transport in this area. A recent joint publication with Willet Kempton (see above) on this subject appeared in the scientific journal “Energy Policy” (“Integration of renewable energy into the transport and electricity sectors through V2G”, June 2008 [see reference list]).
The Netherlands

- **Kema (Netherlands, not-for profit research institute)**
  The ITM project looks at impact and management of electric vehicles on the grid ([www.itm-project.nl](http://www.itm-project.nl)). Bi-directional chargers in electric vehicles will be a part of this study.

Austria

- **International Institute for Applied Systems Analysis (IIASA, Austria).**
  Several studies and publications regarding V2G.

UK

- University of Warwick (UK), research on grid impact of (PH)EVs

V2G demonstrations

United States

- **Six-Month Test by Xcel Energy of V2G and Plug-In Hybrid Electric Vehicles**
  Six plug-in hybrid electric vehicles (Ford Escape PHEVs) will be on the road by the end of 2007 as part of a demonstration test of V2G technology by Xcel Energy.

- **PG&E** has several V2G activities, including working with Tesla motors on a flexible charging strategy. They have also adapted one Prius aftermarket PHEV to feed power back into their system (project by EnergyCS).

- **Willet Kempton is demonstrating an AC Propulsion vehicle** with a 15 kW bi-directional reductive charging system connected as a dispatchable resource to the PJM system.
- **City of Austin + Austin Energy, Texas**
The City of Austin has ambitious plans for a large-scale V2G demonstration. The project is still in the planning phase.

- **Mid-Atlantic Grid-Interactive Car (MAGIC) Consortium**
Proposal by Willet Kempton to supplement DOE PHEV R&D Plan to create a consortium for a very large V2G demo. **Phase I**: ~5 cars + one bus, V2G directly from PJM regulation signal ($1 M in hand), **Phase II**: ~300 cars in PHI, aggregator between PJM and cars, paying A/S contract (about $15 M needed), **Phase III**: Self-sufficient businesses (OEMs, aggregators, ISOs). **Status**: Proposal

- **Ford Motor Company and Southern California Edison** are undertaking a PHEV/Grid study with and have 20 Ford PHEVs under construction for this study (not bidirectional V2G)

- **South Coast AQMD**:
One of the first V2G vehicles was delivered by AC Propulsion to the AQMD (Air Quality Management Department); this vehicle had lead-acid batteries. AC Propulsion’s Plug-In Hybrid Electric Sedan will now be fitted with Lithium Polymer Batteries and new tests and evaluations will be performed.

**Europe**

- **Riso National Laboratory/Technical University of Denmark**
Riso National Laboratory has purchased a Prius PHEV from Amberjac Projects and will convert it to a V2G-capable vehicle for demonstration in its Load Management laboratory (Syslab). In addition, Dong Energy is contemplating a larger fleet test of up to 100 vehicles in conjunction with Riso.

- **V2GUk by the University of Warwick (UK)**
The project called Vehicle2Grid in the UK (V2GUk) will look at the effect of plug-in hybrids on the infrastructure. A single vehicle conversion of a Toyota Prius to a V2G-capable PHEV is foreseen. **Status**: This project seems to be delayed
**Partners**: Amberjac Projects, Ove Arup, Daimler Chrysler UK and E.ON UK

- **Kema/ECN/SP Innovation**: Initial discussions on a V2G demonstration.
PUBLICATIONS RELATED TO VEHICLE-TO-GRID

1. Vehicle-to-grid concept
   More-or-less comprehensive overview of documents available.
   
   a. scientific articles
   b. conference papers
   c. reports
   d. presentations
   e. press articles
   f. books

2. Smart meters
   Documents that provide a general overview of the state of the ‘Smart meter industry’, functional requirements for smart meters and the state of implementation.

3. Ancillary services / grid regulation
   Documents that provide a general overview grid regulation in, especially in the North-West European markets.

Documents with titles in blue are saved on the CD-rom provided with this document. The CD-rom also contains this publication list as an index file, in which the available documents can be retrieved through hyperlinks.

SP Innovation provides these documents under the assumption that SenterNovem’s corporate library has arranged the appropriate entitlements to these documents.
1. PUBLICATIONS ON VEHICLE-TO-GRID

a. Journal articles related to V2G

Turton, H. & Moura, F., Vehicle-to-grid systems for sustainable development: an integrated energy analysis (submitted to Technological Forecasting and Social Change)

Moura, F. & Turton, H., Vehicle-to-grid power generation as a driver of energy system transformation (submitted to Transportation Research: Part D)


Delucchi, M., Lipman, T., An analysis of the retail and lifecycle cost of battery-powered electric vehicles, Transportation research Part D, Volume 6, 2001, p371-404


Kempton, W. and Letendre, S., Electric vehicles as a new power source for electric utilities, Transportation Research Part D 2 3, 1997, p157–175

Lund, Henrik, Kempton, Willet, Integration of renewable energy into the transport and electricity sectors through V2G, Energy Policy, June 2008
b. Conference papers related to V2G


Frank, A., *The plug-in hybrid electric vehicle, for petroleum displacement, reduction of co2, electric grid economics, - system implications and direct use of renewable energy*, presented at the 23rd International Battery, Hybrid and Fuel Cell Electric Vehicle Symposium and Exhibition (EVS-23), Anaheim, 2-5 December 2007


Rahman, S.& Teklu, Y., *Role of the electric vehicle as a distributed resource*, Power Engineering Society Winter Meeting, IEEE, Volume 1, Issue , 2000 Page(s):528 - 533 vol.1

Kempton, W., Letendre, S., *Electric vehicle value if integrated with the utility system*, Presented at Transportation Research Board 78th Annual Meetings, 11 Jan 1999, Washington, DC

c. Reports related to V2G


Kurani, K., Heffner, R., Turrentine, T., *Driving Plug-In Hybrid Electric Vehicles: Reports from U.S. Drivers of HEVs, converted to PHEVs, circa 2006-07*, Plug-in Hybrid Electric Vehicle Research Center, Institute of Transportation Studies, 2007, University of California, Davis


Moura, F., *Driving energy system transformation with “vehicle-to-grid” power*, IIASA Interim Report IR-06-025, June 2006, part of Phd work


Schluchter, C., *Die Idee des Vehicle to grid (V2G)*, D-ITET, PPS Arbeit, EEH – Power Systems Laboratory, ETH Zürich, Juni 2007
d. Presentations on V2G


Dirk Uwe Sauer (RWTH Aachen University), *Technology and transition scenarios on the road to 2050 - which energy carriers are needed and how to include the mobility sector*, Second International Renewable Energy Storage Conference, Bonn, 19-21 November 2007


Ariel Liebman & Geoff Walker, *Vehicle-To-Grid: Plug-In Hybrids will save the electricity system and the climate-system*, Complex ’07, July 2007


Willett Kempton, *Vehicle to Grid Power as Wind Storage*, November 2006


Eugene Nishinaga (Manager of Research and Development, SF BART), *Vehicle to Grid (V2G) to Support BART Electrical Demand*, ZEV Technology Review Requested by the Air Resources Board, September 26, 2006

Filipe Moura, *"Vehicle-to-Grid" Energy Systems: The potential to influence the energy mix*, IIASA’s Young Scientists Summer Program presentation, 2005

Willett Kempton & Jasna Tomic, *Using Electric Vehicles for Grid-Connected Storage*, Energy and Nanotechnology-Storage and The Grid, Rice University, 16 Nov 2005


Willett Kempton, *Vehicle to Grid Power*, The Seattle Electric Vehicle to Grid Forum, June 7, 2005

Amardeep Dhanju & Phillip Whitaker, *V2G and Wind Power*, Seattle V2G Technical Symposium, June 6, 2005

Alan Cocconi & Tom Gage (AC Propulsion, Inc), *Connected Cars: Battery Electrics & Plug In Hybrids*, The Seattle Electric Vehicle to Grid Forum, V2G Technical Symposium, June 6, 2005

Tom Gage (AC Propulsion, Inc), *EVs Without OEMs*, The Seattle Electric Vehicle to Grid Forum, V2G Technical Symposium, June 6, 2005


Frank C. Lambert (Chair of Hybrid Electric Vehicle WG of the IWC), *Standards for V2G Interconnection to the Grid*, Seattle V2G Technical Symposium, June 6, 2005


Dr Geoff Walker (Sustainable Energy Research Lab, School of Information Technology and Electrical Engineering, University of Queensland), *Hybrid Electric Vehicles meet the Electricity Grid: Plug-in Hybrids (PHEVs) & Vehicle to Grid (V2G)*
e. Press articles on V2G


Denver Post, p. C.1., October 23 2007, *Xcel to test plug-in cars as power source*

Green Car Congress, 22 October 2007, *Xcel Energy Announces Six-Month Test of V2G and Plug-In Hybrid Electric Vehicles*

Green Car Congress, 5 October 2007, *Software Startup Targets Vehicle-to-Grid Management*


San Francisco Chronicle, p. A.1, July 20 2007, *Cleaner future? Plug in / electric hybrid cars hold promise of slashing greenhouse gases*

Smart Grid Newsletter, May 28 2007, *Vehicle to Grid: Threat or Opportunity?*

Smart Grid Newsletter, May 28 2007, *V2G Primer for Utilities*, Alex Zhang

Los Angeles Times, p. C.2, April 28 2007, *A two-way street with these hybrids*


The Christian Science Monitor, p. 09, Februari 12 2007, *Plug-in hybrids: the way to reduce emissions and foster energy independence; Their commercial success hinges on an aggressive development and marketing effort by a major automaker*, Steven Letendre, Paul Denholm, Peter Lilienthal


Geotimes, Volume 50, Issue 8, August 2005, Pages 24-27, Penney, T., Elling, J., *The race to connect cars, communities and renewables*

The Christian Science Monitor, p17, July 29 2004, *Electric cars that pay*

The North American utilities business magazine, V140, no. 4, 2002, p16, *The V2G Concept: - A New Model For Power?*, Steven E Letendre, Willett Kempton,

2. SMART METERING DOCUMENTS


Metering.com, 9 July 2007, *Norwegian energy regulator NVE recommends smart meters for all customers in Norway*


Letter to the Dutch Parliament from the Dutch Ministry of Economic Affairs, *Policy intention to the Lower House on the structuring of the meter market for small energy users*, 10 February 2006


Presentation by John Parsons, Senior Project Manager, Project Coordinator, European Smart Metering Alliance