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Executive summary

This report summarizes the activities and accomplishments of a two-year DOE-funded project on Grid-Integrated Vehicles (GIV) with vehicle to grid power (V2G). The project included several research and development components: an analysis of US driving patterns; an analysis of the market for EVs and V2G-capable EVs; development and testing of GIV components (in-car and in-EVSE); interconnect law and policy; and development and filing of patents. In addition, development activities included GIV manufacturing and licensing of technologies developed under this grant. Also, five vehicles were built and deployed, four for the fleet of the State of Delaware, plus one for the University of Delaware fleet.

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Fundamental technical concept

In the United States, passenger vehicles are, on average, driven about 1 hour a day – the remaining 23 hours they are parked, most often either at home or at work. The average distance driven each day is around 30 miles. However, a typical electric vehicle (EV) has a range of about 100 miles, meaning that on most days, there would be around 70 miles worth of battery capacity left in the vehicle. Further, to perform adequately at highway speeds, electric vehicles require a drive train output of 100 kW. Thus, the vehicle electronics are already sized for power output at levels above standard AC vehicle connections. Thus, most vehicles are parked most of the time, and existing vehicle systems can draw or provide substantial power available to and from the grid.

A grid integrated vehicle (GIV) is an EV with built-in communication and control software that allows it to interact with the electric grid. A GIV with vehicle to grid capability (V2G) can additionally provide power from its battery, through its existing drive electronics, back to the grid. That is, GIV refers to control by the grid operator (of charging and/or discharging), V2G refers to the additional ability to discharge to the grid. An aggregated fleet of GIVs has the potential therefore to store a large amount of energy. If the entire US light vehicle fleet of 200 million vehicles were V2G-capable (at 15 kW per vehicle), then the total amount of power that could be provided would equal 3,000 GW. This amount is three times the current US generation capacity (1,000 GW) and six times the country's load (450 GW). This project developed, built, and tested vehicles with both GIV and V2G capability, as the latter is more challenging for both technical, standards, and OEM comfort reasons. The systems and regulatory systems tested here can be used for either GIV with charging capability only, or for GIV with V2G.

GIVs provide storage at the low-voltage end of the distribution system. A 15 kW grid connection and a per vehicle storage capacity of 30 kWh means that GIVs are only capable of short discharges/charges and are thus better suited to capacity markets – not providing baseload power. However, given that GIV is a secondary use of customer equipment (the primary use of course being transportation) means that a GIV system would have very low capital costs – essentially just the on-board GIV control and communication equipment, currently around \$400. The operating cost for such a system is the payment to the drivers as an incentive to remain plugged in, plus compensation for any additional battery wear. We estimate that payment for incremental equipment and compensation for wear (not including driver incentive nor management and operations), for an EV with a 15 kW connection and a 30 kWh storage capability, the capacity cost would be \$27/kW and the storage cost \$13/kWh. Both figures are at least an order of magnitude less than purpose-built battery storage systems. The capacity cost (per kW) is two orders of magnitude less than any known utility-scale energy storage system (including CAES and pumped hydro).

Driving Pattern analysis

To design GIV systems, we needed to understand driving patterns. Driving patterns determine required range for different trips throughout the day, and times of driving determine times the GIV is not available for grid services.

We obtained data on the driving patterns of nearly 500 vehicles from a database with 1-second resolution, continuously tracked over three years by Georgia Tech. To obtain access, we needed to conform to rigorous privacy and human subjects requirements, including use of the data only at a remote site. We and our research partners developed software to collapse this data base into trips over one year, each with start time, end time, and distance driven. Our software also tried to identify the trip terminus— specified as “Home”, “Work”, or “Other”. Separately from the trip data, surveys were used to elicit demographic information about the household to which the vehicle belongs. Households were selected for the study to be representative of the diversity of demographics, and locations within the study area, consisting of the urban and suburban counties in and around Atlanta, GA.

We used the trip data to quantitatively answer questions relating to two different areas of concern about the potential widespread adoption of plug-in electric vehicles. The first relates to the ability of electric cars, to satisfy the transportation needs of American drivers (assuming limited range and slow refuel, both of which may improve over time). The second is the effect that these vehicles could have on the electric system. We calculated the effects that different battery sizes (vehicle electric ranges), plug sizes (charge rates), charging algorithms, and infrastructure (e.g. public charging) will have both driving and the electric system. Cars with every combination of these parameters were tested against the driving and parking cycle experienced by each car in the dataset. This allowed us to conclude both the driving suitability and the electrical value of different electric cars and charging algorithms in a more realistic and quantitative way than has previously been attempted.

Variables

Battery and Plug: We used a virtual test-fleet of diverse electric cars with a distribution of battery capacities and plug sizes. The range of battery sizes under investigation would give electric vehicles (EVs) ranges from approximately 10-400 miles. The range of plug sizes in the tests represents vehicles with the ability to only plug in to a 120 Volt, 10 Amp household outlet, through the SAE J1772 standard at 44 kW, up to an IEC standard 62196-2 three phase connector at 44 kW.

Charging Algorithm: Six charging algorithms were simulated. The first charging algorithm was to simply charge as soon as the vehicle is plugged in (as soon as the trip is over), and charge at the maximum rate possible until the battery is full or the next trip begins. The second charging algorithm did charge the car except between the hours of midnight and 7:00 am, then charged at the maximum possible rate. The third charging algorithm charged at half of the maximum rate during the day, and at the full rate between midnight and 7:00 am. The fourth charging algorithm only charged the battery up to half of its maximum charge capacity during the day, and the rest of the way starting at midnight. The fifth and sixth charging algorithms assumed perfect prediction of driving needs and put just enough energy into the battery for the upcoming trip. The fifth

charged the battery at the maximum rate ‘at the last minute’, while the sixth charged at a constant rate while the vehicle was parked, usually at less than the maximum rate possible.

Charging Infrastructure Deployments: Simulations were performed assuming each of three levels of vehicle charging infrastructure development. The first level assumed that vehicles will only be able to charge when they are at home. The second level assumed that vehicles will be able to charge both at work and at home. The third level assumed that vehicles will be able to charge anywhere they stop. While intermediate or alternative infrastructure development models would be interesting to test, “Home”, “Work” and “Other” were the only trip terminus inferred for this dataset.

Inquiry

Processing: For each charging algorithm, infrastructure set, plug size and battery size, a simulated EV with these characteristics was “driven” through the use patterns of each of the cars in the dataset. When the car was driving, the state of charge (SoC) of the battery was reduced according to the distance covered down to a minimum value greater than or equal to zero. When the vehicle was charging the SoC increased according to the size of the plug, the charging algorithms, and the infrastructure, up to a maximum value of the battery size.

EV range failures: From the resultant SoC history, we identified individual trip failures by counting the number of occasions on which the SoC dropped to zero. This “failure count” was the number of occasions on which the EV would not have been used or would have left the driver stranded on the roadside, or the number of occasions on which an EV owner would have rented or borrowed another vehicle for that trip.

We performed a second analysis of this failure rate by calculating the total mileage covered each day and total number of minutes spent plugged in, for each day in the year, for each vehicle in the dataset. For each vehicle’s plug size and battery size, the ratio of time parked to distance covered was used to determine whether the vehicle could accomplish that day’s driving. Each failure was a day on which the EV driver would have had to rent another vehicle.

It should be noted that both of these analysis produced conservative numbers, since most households have more than one car, and on some occasions when the EV would not suffice and a failure was counted, a real owner could very simply choose to take a different vehicle, or modify their planned route. Compensating for the second car factor is theoretically possible with this dataset since the household information includes the number of cars owned, but was not attempted. We have no way to simulate adaptation by the driver to a low-range vehicle. Both these factors imply that our results will tend to overestimate range problems from this gasoline-vehicle dataset.

The objective of both of these failure analyses was twofold: we wanted to know how much driver behavior would have to change to use an EV, and we wanted to know the trade-offs between increasing charging line power capacity, battery energy capacity, and vehicle trip functionality.

The figures below present the trip characteristics from our analysis. Figure 1 displays the number of days, on average, that a particular distance is driven. As can be seen from the graph, the vast majority of journeys are less than 100 miles. This finding is better illustrated by Figure 2 which shows the fraction of the fleet that never exceeds a certain number of miles. From looking at Figure 2, it is possible to see that 8% of the fleet never exceed 100 miles and 18% never drive further than 150 miles in one day.

Figure 1: Number of Days a Distance is Driven (from Pearre et al 2011)

Figure 2: Maximum Daily Miles (from Pearre et al 2011)

More detailed results using the above data and methods are presented in Pearre, Kempton, Guensler, and Elango, 2011, *Electric Vehicles: How Much Range is Required for a Day's Driving?* In press for *Transportation Research Part C*.

Market for EVs and their Attributes

In order to better understand the potential market for both electric vehicles and GIVs, we developed, pretested, and administered a vehicle choice survey to a representative sample of 3029 respondents across the United States. The questionnaire included three types of information: questions, explanations and choice exercises. Questions included the

households' vehicle inventory and use, vehicle purchase intentions, demographic questions and attitudinal questions. Explanations included how regular EVs work and how V2G vehicles and contracts might work. This information was included to help respondents make informed decisions. Choice exercises were designed to elicit vehicles choices, including comparison of EVs with different attributes against their current gasoline vehicle, and also EVs with V2G and without.

Given the nature of the survey – asking respondents to choose between different options – we used a conjoint survey design. This approach provides respondents with a number of choice scenarios, each containing three different types of vehicle. The vehicles differed by price, range, charging time, and the level of commitment required to participate in the V2G ancillary services market. The combination of a number of choice scenarios and various vehicle choices allowed data to be collected for a wide range of EV attribute combinations. We implemented the survey as a web form (using qualtrics.com) rather than through the mail or via the telephone. The number of choices the respondents are asked to make would have resulted in a telephone survey being impractical – the respondents really needed to see the various choices before them. While a mail survey could have been used, there were further advantages to conducting the survey online. We began the survey by asking respondents about their current vehicles and plans on future purchases, then some subsequent question attributes were changed based on their respondents' initial answers. One disadvantage of an internet sample is that it tends to oversample females and young people. To account for this we weighted the responses to ensure the sample was representative of the US population.

For the V2G questions, respondents were asked to select among both EV attributes and V2G contract terms and requirements. We were particularly interested in how consumers make tradeoffs involving features of the car and requirements and benefits of the contract. Discrete choice models were used to analyze the data. The survey: 1) considered customer's valuation (willingness to pay) of the different features of plug-in cars (e.g. driving range, time needed to recharge, value of fuel backup, and overall fuel cost); 2) identified V2G contract term features acceptable to consumers (e.g. the number of hours the owner is required to be connected to the grid, and the minimum range that the owner is guaranteed); and 3) forecasted market share of V2G cars under different policy scenarios.

Since the survey was part of the DOE funded work, which included deployment of two additional EVs plus provision of four EVs for the State of Delaware, we were probably able to make the questions more realistic than would a survey group not driving and supporting EVs for a number of users. Nevertheless, before administering the survey, we conducted four rounds of face-to-face question pretesting, then web pretesting, to ensure the questions were clear, captured important elements, and were unbiased. During the course of the pretesting a number of variables were dropped and added, both to tighten up the survey design and ensure that the data we wanted was collected. In the full web survey sample, 3,029 responses were collected.

The latent class analysis allows us to identify one group more inclined to purchase gasoline vehicles, another more inclined to purchase an electric vehicle. Based on this analysis, we labeled separate "GV class" and the "EV class". Since we found the EV

class is about 40% of consumers, and since it will be many years before EV production could even approach 40% of new car production, we concentrate here more on the EV class. That is, they are presumably the sole buyers of EVs for at least a decade. Tables 1 and 2 below present two key findings from the survey. Table 1 shows the amount that people are willing to pay for an increase in driving range (relative to a base of 75 miles). As can be seen, people in the EV class are willing to pay a substantially higher amount for an increase in range.

Table 1: Willingness to pay for range increments relative to 75 miles, compared to battery cost to provide that range. (First three columns from Hidrue et al 2011).

Range	Survey responses		Calculated battery cost	
	GV Class	EV Class	Incremental battery cost @ \$500/kWh	Incremental battery cost @ \$300/kWh
75 mi	\$0	\$0	(base)	(base)
150 mi	\$3,894	\$7,349	\$9,375	\$5,675
200 mi	\$5,723	\$12,757	\$15,625	\$9,375
300 mi	\$7,670	\$17,748	\$28,125	\$16,875

However, the amount they will pay extra is today less than the cost of batteries to provide this extra range. The rightmost two columns shows the cost of batteries to provide the extra range, calculated with a relatively light and efficient sedan at 250 wh/mi. Thus, for DOE 2012 goal of \$500/kWh, that is \$125 per extra mile of range. For DOE 2014 goal of \$300/kWh, that is \$75 per extra mile of range. The resulting battery cost calculations are shown in Table 1, last two columns.

What we observe is that, to the GV class of buyers, under all scenarios, they will not pay as much for extra range as the extra range would cost. Even for the EV class, at \$500/kWh battery cost, their willingness to pay is not sufficient to justify any larger batteries (of course the EV class is a distribution and some individuals would do so). At the 2014 DOE goal of \$300/kWh, the EV class is willing to pay more than the cost of batteries to provide 150 or 200 miles of extra range, but not as much as the battery cost for 300 miles of extra range.

Table 2 presents similar data for charging time – How much would people pay more for a car that could charge quicker? In this case the base of comparison was 10 hours charging time to achieve 50 more miles of driving (50 miles at 300 wh/mi is ~15 kWh).

Table 2: Willingness to pay for faster charging time required for 50 miles range, relative to 10 hours (first three columns, from Hidrue et al 2011), compared with cost for faster charge (last two columns, estimated here).

Charge Time	GV Class	EV Class	Incremental device cost	Strategy for charger engineering
10 hours	\$0	\$0	(base)	110 VAC 12 A charger on board
5 hours	\$4,720	\$971	\$600	208/240 VAC and larger components in charger for 4 kW
1 hour	\$5,900	\$7,626	-\$800	Use drive train to charge, 19 kW
10 min.	\$6,490	\$11,093	\$50,000	Station DC charger at 150 kW

Table 2 shows that people in the GV class will pay more to drop charging to 5 hours (from 10 hours) than people in the EV class, the latter group assigning this only \$900 value. The EV class will pay more to in further decreasing the charge time to 1 hour or 10 minutes. We interpret this as the EV class being more thoughtful about EV needs, as a decrease from 10 to 5 hours would not really help that much, since a 5 hour charge is still too long for a meal or an en-route stop. In our view, having driven EVs for several years and worked through trip limits and en-route charging strategies, there is little difference between 5 and 10 hours as both would be accomplished during an overnight (or possibly at-work) charge. However, when the charge time decreases to an hour or less, there is a significant value to the driver—a one hour charge can be accomplished during a short break on a long drive, practical as a stop for a meal or to look at a local attraction. Going further, a 10 minute charge is close to the time it takes most people to fill up a gasoline vehicle.

In the last two columns of Table 2, we suggest engineering approaches to decreasing charge time, and the cost of each. Unlike incremental battery cost in Table 1, the cost of achieving faster charging non-linear, in fact, it is non-monotonic. At the transition from a separate charger to modifying the drive power electronics for charging integrated with the drive train, there is a substantial negative cost (elimination of a ~\$1200 separate charger while adding \$400 of components in the drive electronics¹). An off-board DC charger allows very high rates of charge but may require extra battery cooling on board and/or additional electric service upgrades; here we count only the approximately \$50,000 for a 150 kW off-board DC charger itself.

¹ The \$400 cost of components for the 20 kW integrated charger/discharger includes contactors, power line filters, fuses, control board and connectors, and the motor insulated coupling, at production quantity of 10,000 vehicles. This replaces an estimated \$1200 separate charger rated at lower power (e.g. 4 to 6 kW) and only charging (source: Paul Carosa, VP Engineering, AC Propulsion, email of 23 April 2011).

In summary, the market analysis study demonstrates that there is a small but viable market for 100 mile range electric vehicles today. The amount that even the EV class is willing to pay for high range is above the 2012 goal's cost of batteries to provide that range, so the existing Federal subsidy appears to be important to expand this early market. We find that potential EV buyers are willing to pay for a 10-20 kW charge rate at values well above the cost of providing that rate, feasible with a 40-80 amp, 240 volt connection. At a power level in that range, previous analysis has demonstrated that ancillary services can gross approximately \$3,000 per vehicle per year in high value markets (Kempton and Tomic 2005). However, independently of any V2G value, our finding is that drivers are willing to pay for high charging power levels as in 20 kW, simply for driving convenience.

The first set of results, on choice of EVs against gasoline vehicles, and value of EV attributes (as in the tables 1 and 2 above) are in press as Hidrue, Parsons, Kempton & Gardner, *Willingness to Pay for Electric Vehicles and for their Attributes*, cited in the "Publications and reports" section below.

Manufacturing

One key to the success of the project was developing a manufacturing partner so that we would have vehicles that can become Grid-Integrated Vehicles. At the suggestion of the Delaware Economic Development Office we approached AutoPort, Inc., a GM-Certified, Tier 2 Upfitter based in New Castle, Delaware. AutoPort is capable of processing 250,000 vehicles per year, from complete rebuilds (ambulance, rail/truck, etc.) to light processing such as undercoating and paint protection. For an electric retrofit, using current equipment, at their current facilities, they can produce up to 1,000 electric vehicle conversions per year.

Facilitated by the University, a memorandum of understanding was signed between AutoPort and AC Propulsion (the company which designed the eBox and manufactures the power electronics, motor and controls for the vehicle). Senior AutoPort assembly engineers went to AC Propulsion's headquarters in San Dimas, CA, for training in electric vehicle conversion and diagnosis (paid by the state of Delaware for blue collar training, not DOE). AC Propulsion also sent engineers to AutoPort's Delaware facility to oversee conversion of the first batch of vehicles. The training visits were funded by a \$94,140 grant from the Delaware Economic Development Office funds leveraged because of the current grant. As a result of this project there now exists a manufacturer capable of producing quantities of V2G-capable electric vehicles.

Additional vehicles converted by AutoPort subsequent to this award include: a light duty van suitable for use by commercial fleets, a US Postal Service LLV, now delivering mail as part of a USPS field trial, and a vehicle ordered by and soon to be exported to Denmark for GIV experiments there (the PI is working with Danish Technical University and Energinet.dk on this).

Four eBoxes converted by AutoPort are currently being used by the Delaware state fleet, and provide V2G services when parked. The installation included high power plugs at

two different state fleet locations (two in Dover and two in Wilmington). Subsequent to the grant period, the Delaware state fleet ordered upgrades to J1772 charging inlets on these vehicles at the fleet operator's expense.

Figure 3: AutoPort after Development of EV Conversion Facilities

GIV Component Research and Development

The University has developed three separate components of the GIV system: the Vehicle Smart Link (VSL); V2G-capable Electric Vehicle Supply Equipment (EVSE); and the aggregation server.

Vehicle Smart Link

For an EV to operate as a GIV, there needs to be an intelligent onboard system that can communicate with the aggregation server, monitor vehicle systems, and control charging (and optionally discharging). The Vehicle Smart Link performs these tasks – it controls charging, reports to the server, and either knows or attempts to predict the next trip. It obtains the grid location and authorizations from the EVSE and reports battery capacity to the aggregator.

Iteration 1 of the VSL was an automotive-grade linux box that was installed underneath the dashboard. Iteration 2 is a UD-designed microprocessor board, plugged into an ARM linux board, the latter designed for embedded applications. Mounting, ideally, is accomplished with the two-board VSL mounted inside OEM enclosures on the vehicle. Figure 4 shows Iteration 2 of the VSL, embedded in a manufacturer's drive power electronics unit. The UD board can generate or parse the J1772 control signal, serial and/or CANbus to the vehicle controls, and has a J1772 compatible inband signal used for communication between EVSE (building) and VSL (vehicle) over the existing standard J1772 pilot connection. Thus, the EVSE and vehicle communicate without any new cable or new connection, and without reliance on wireless.

We have set up automated charging and V2G control of the cars based on a predicted or scheduled "next trip". A future trip consists of a date and time, an expected driving distance until return to an EVSE, and a text description of the destination. Our original design was to have the next trip able to be set in four ways:

1. The user (driver) may make a trip reservation in an online calendar.
2. The user may enter or correct the next predicted trip using a touchscreen in the car.
3. The car has a “minimum range”, specified initially by the driver. The VSL tries to always maintain this much range, independently of expected next trips.
4. The prediction software may predict the next trip based on the previous driving history of the user.

Methods 1, 2 and 3 are functional. We attempted to implement method 4 under this award, but it proved too difficult to implement reliably, within our funding and time limits, for actual vehicle use.

Regardless of the source of the expected next trip, the VSL in the car insures that there is sufficient charge available for the next trip. When first plugged in, the VSL inspects whether the minimum range is available and if not, charges to that level initially. Then, the VSL computes the amount of energy needed for the next trip (based on the expected trip miles) and computes the time needed to charge the batteries up to that energy level based on the current plug power capacity. The VSL then begins providing V2G capacity to the grid, and, when charging for next trip is needed, it automatically switches from V2G mode to straight charge mode.

The VSL also collects information from the vehicle management system (VMS) while the car is being driven or charged. This data includes information about the cell voltages, cell temperatures, current flow while driving, etc. This can be used for diagnostics, independently of any GIV/V2G use. For GIV functionality, we expect to use it to automatically calibrate the batteries in the future.

Figure 4. A commercial EV drive power electronics unit (AC-150), with UD's VSL installed (red circle). The wiring harness connections to the VSL are not shown.

Electric Vehicle Supply Equipment

While a number of manufacturers have designed and produced EV charging stations, none had the integrated controls needed for GIVs. We thus decided to design our own EVSE to provide the required controls for GIVs with V2G. Our design specification was for an EVSE that would comply with the SAE J1772 standard, but also store both V2G authorization and the EVSE's grid location (to provide information about the nearest distribution transformer, feeder etc.). To enable safe backfeeding, the grid location had to be 100% accurate. The GIV connects to the EVSE through a single wire that transmits both power and data. This system insures that the grid location, authorization for backfeeding, etc are at a fixed point in the electrical system, even if the vehicle can move across electrical connection points.

We developed specifications, designed, and fabricated a prototype EVSE/EV charger controller board which implements the SAE J1772 standard for electric vehicle charging. The electronics consists of two main boards: a microcontroller board and a daughter board. The daughter board has the components and discrete parts that implements the electrical and signaling requirements for J1772. Because the standard requires the uncommon signal voltages of positive and negative 12 volts, special circuits were used to reliably communicate. In addition, the daughter board uses USB to communicate with the VSL. Both the vehicle management system serial interface and the microcontroller serial interface are sent over a single USB port which then gives the operating system two virtual serial ports to interface with each device. Also, the daughter board provides the power control circuitry to enable the VSL only when the VMS is active replacing the existing relay control board. The prototype is currently being field tested.

Figure 5. EVSE field test unit. UD-designed boards are at upper right (J1772 and in-band communications to vehicle) and lower left (GFCI and relay driver).

Vehicle Aggregation Server

Independent System Operators (ISO - the organizations which manage the electricity grid) typically have a minimum requirement for a provider of ancillary services. In the PJM service area the minimum is 500kW. For GIVs to operate in the ancillary services market, the individual power output of each vehicle (up to 19 kW) needs to be aggregated together to create an amount of power sufficient to make the contract minimum of the ISO. For frequency regulation in PJM Interconnection, the minimum size is 500 kW (1/2 MW), and symmetrical up and down regulation are required. Aggregating GIVs takes multiple small and only partially predictable storage resources, and makes the aggregate into a single, large, stable, and reliable power source. The aggregator bids capacity into the ancillary services market, it then dispatches the request to the individual vehicles and reports the actual amount of power dispatched.

The aggregator software is designed to manage the complexity inherent in an operational V2G system. It ensures that each vehicle has enough charge for the next trip and uses that data to calculate how much remaining capacity is available to offer in the market. The system also has the ability to aggregate and dispatch cars in multiple ISOs using a single coalition server. To allow a person to easily view to the data collected by the coalition server we have designed a web interface which updates in real-time (Figure 6).

Figure 6: Coalition Server Web Interface

From an ISO perspective, the end result is no different that if the power were being provided by a traditional generator – except that the power is delivered much faster and more efficiently.

Testing of a single vehicle shows that the power response from vehicle V2G systems closely follows the command signal (see Figure 7) and responds with a higher fidelity than rotating generation equipment.

Figure 7: Response by a single vehicle V2G System (from Kempton et al 2009)

Interconnect Policy

In order for GIVs to backfeed power into the grid, the locations at which they are operating must first be certified by the local electric utility. Interconnection approval is required for any generation or storage device that is capable of backfeeding electricity to the grid from a customer site. It requires testing of the device to IEEE standard. These protections are required on all customer-site generation in order to protect linemen (utility workers). After utility approval and inspection, and if necessary, the meter at the interconnection location could be swapped out enabled to run bidirectionally. (The old electromechanical meters read bidirectionally without any additions.) The location with “customer sited generation” is then typically added to the utility’s database of distributed generation sources that is used to prepare utility line workers for jobs.

During the course of this project, the University’s eBox became the first electric vehicle with V2G capability to be certified in this way. The City of Newark Electric Department, a municipal utility in Newark, Delaware, approved and signed the certification on January 14, 2009. Certification with Delmarva Power followed shortly thereafter meaning, between the IOU and Munis, that meant that GIVs had been approved to perform V2G services in 90% of Delaware.

While interconnection certification is legally required for V2G, there is another piece of legislation which is important for the financially viable operation of a V2G system – net metering. Without net metering laws in place, a vehicle owner would not receive equal value on the power drawn from and sent to the grid. Owners would pay retail rates when charging their vehicles but only receive wholesale rates (typically 5-10 cents less per kWh) when discharging power. In June 2009, the Delaware legislature passed a bill, SB

153, requiring electric utilities in the state to net meter Grid Interactive Electric Vehicles with V2G technology. Under this law, utilities credit customers for energy at the same retail rate that they pay to charge the vehicle. An amendment to the bill was added at the suggestion of the utility which provides them flexibility in developing more creative tariff structures to encourage the use of this technology, such as time of use rates. The University's research team participated in the legislative process by providing technical and policy recommendations and support to legislators and their staff. Additionally, the University's electric vehicle demonstrated V2G on the stairs of Legislative Hall to give public officials a better idea of what this technology entails.

Specific End Products of Funded Activity

Patents

Patent applications stemming from this work:

- US patent application publication No. "Hierarchical Priority and Control Algorithms for the Grid-Integrated Vehicle", filed 3 March 2009, application 12/397,030. (Patent assignee, University of Delaware; inventor, W. Kempton).
- Electric Vehicle Station Equipment for Grid-Integrated Vehicles. Serial 12/887,013, filed 21 Sep 2010 (Kempton, Kiamilev, McGee, Waite) (UD 307)
- Electric Vehicle Equipment for Grid-Integrated Vehicles. Serial 12/887,038, filed 21 Sep 2010, UD10-24 (Kempton) (UD 308)
- Aggregation Server for Grid-Integrated Vehicles. Serial 12/887,064, Filed 21 Sep 2010. (Kempton) (UD 314)

Additionally the University has authorized one licensee to utilize our VSL technology and one to use our aggregator technology. Additionally, the University is currently in license negotiations for the EVSE, a second VSL, and for a second aggregator.

Electric Vehicles Deployed

Five vehicles were manufactured by Autoport, Inc, of New Castle, Delaware. Four are in use by the State of Delaware fleet, and one by the University of Delaware. These are converted from gasoline Toyota Scion XBs, using a conversion design engineered by AC Propulsion. They have 35 kWh Li-ion battery packs based on 18650 cells, and a 150 kW traction drive using the AC-150 power electronics. These are highly usable utility vehicles which seat 5 plus cargo, have a maximum speed of 90 mph (manufacturer claim; not tested under this award), and a practical range of 120 miles. The grid interface can charge or discharge at a rate of 19.2 kW at 240 VAC and in optimum conditions (mid-range battery state of charge and moderate temperatures).

Laws and approved interconnects

City of Newark Electric Department approved and signed the certification for “customer-side generator”, approving V2G backfeeding at 19.2 kW, on January 14, 2009.

Delmarva Power, Interconnect agreement for AutoPort Inc., New Castle, for customer-side generator, 2009.

Delaware law, Senate Bill 153, AN ACT TO AMEND TITLE 26 OF THE DELAWARE CODE RELATING TO CUSTOMER SITED ENERGY RESOURCES. (Primary Sponsor: Simpson, Additional Sponsor(s): Rep. Kowalko, CoSponsors: Sen. McDowell, Sokola, Sorenson; Rep. Hocker), Introduced: 06/16/2009, signed 09/21/2009. Synopsis: This bill prepares Delaware for a new technology, grid-integrated electric vehicles with vehicle-to-grid power. This technology provides electrical storage and other services to the grid; it does not generate new power and thus over time will not receive a net credit due to net metering.

Publications and reports

2011 Michael K Hidrue, George R Parsons, Willett Kempton, Meryl P. Gardner, "Willingness to Pay for Electric Vehicles and Their Attributes" Final proof posted online, *Resource and Energy Economics*, doi:10.1016/j.reseneeco.2011.02.002

2011 N. S. Pearre, Randall L. Guensler, Vetri V. Elango , "Electric Vehicles: How Much Range is Required for a Day's Driving?" final proof posted online, *Transport. Res. Part C* (2011), doi:10.1016/j.trc.2010.12.010.

2009 Willett Kempton, Victor Udo, Ken Huber, Kevin Komara, Steve Letendre, Scott Baker, Doug Brunner, & Nat Pearre , "A Test of Vehicle-to-Grid (V2G) for Energy Storage and Frequency Regulation in the PJM System: Results from an Industry-University Research Partnership" Report, distributed by CCPI, UD. November 2008, revised Jan 2009. 32pp. (Developed primarily under earlier funding from PHI and Google.org.)

2011 Nathaniel Pearre, Willett Kempton, Randall Guensler, Vetri Elango , n.d. "Charge Rate and Driving Range of Electric Vehicles: Substitutability of Charging Power for Battery Energy" (provisional title) (manuscript, under revision)

2011 Kamboj, S., Kempton, W. and Decker, K., "Deploying Power Grid-Integrated Electric Vehicles as a Multi-Agent System", to appear in the Proceedings of the Tenth International Joint Conference on Autonomous Agents and Multiagent Systems (AAMAS 2011).

2010 Kamboj, S., Decker, K., Trnka, K., Pearre, N., Kern, C. and Kempton, W., "Exploring the formation of Electric Vehicle Coalitions for Vehicle-To-Grid Power Regulation" , in 2010 AAMAS workshop on Agent Technologies for Energy Systems (ATES@AAMAS 2010).

Standards body proposal

Proposal SAE J2931/5, "In-band signaling using negative side signaling", proposal to SAE J2931 Committee, proposed 21 January 2011.

Presentations

The following presentations reported on the funded activity described above.

- 2011 "Integrating a High Fraction of Offshore Wind into the Electric Grid" Invited lecture for "Power Event", Danish Technical University, Center for Electric Technology, Lyngby, Denmark.
- 2010 "EV as a Distributed Generator" Invited presentation to Maryland Public Service Commission Technical Conference on Electric Vehicles" 22 October 2010, Baltimore, MD.
- 2010 Exploring the formation of Electric Vehicle Coalitions for Vehicle-To-Grid Power Regulation, (with Kamboj, S., Decker, K., Trnka, K., Pearre, N., Kern, C., presented by Kamboj) 9th International Conference on Autonomous Agents and Multiagent Systems Workshop on Agent Technologies for Energy Systems. 10-14 May, Toronto, Canada.
- 2010 Keith Decker and Sachin Kamboj, "V2G: Electric Vehicle Coalitions for Vehicle-To-Grid Power Regulation", presented at CompSust'10: 2nd International Conference on Computational Sustainability, Boston, MA
- 2010 "The Grid Integrated Vehicle (title?)" Invited Panel speaker, EPRI/PJM Energy Storage Summit. 20 April, Valley Forge, PA.
- 2010 "Implementation of the Grid Integrated Vehicles, with Vehicle to Grid Power" Invited presentation for "EERE Analysis Seminar" at US DOE and webinar, sponsored by the office of Planning, Budget & Analysis, 17 March 2010.
- 2010 "Vehicle Integration and Manufacturing Issues" Briefing for panel, "The Role of Electricity as a Transportation Fuel", invited by Environmental and Energy Study Institute, Rayburn House Office Building, Washington DD, 15 March 2010.
- 2010 "2010 "Vehicle to Grid Power" AAAS Annual Meeting, 18 February, San Diego, CA. (This symposium and the associated AAAS press conference on new V2G developments got worldwide press coverage.)
- 2009 "Green Growth and the Blue Economy" Invited (plenary) Lecture, 3rd International Symposium on EXPO 2012, Yeosu Korea. At Jeju, Korea, 19 November 2009.
- 2009 "Plugging Electric Vehicles into PJM for Ancillary Services" MACRUC 2009 (Mid-Atlantic Conference of Regulatory Utilities Commissioners) 22 June 2009 (similar presentation before Delaware PSC, 7 July 2009)
- 2009 "Dispatching Electric Vehicles to Provide Regulating Power and Reserves" Invited keynote to JIEEC 2009 Jornadas Internacionales de Equipos Eléctricos, International Electrical Equipment Conference, Bilbao, Spain, 25 & 26 May 2009. Also, invited presentation to ENDESA Advanced Business Strategies Dept, other ENDESA managers, and Technalia staff, Madrid, Spain, 27 May 2009.
- 2009 "Will the Concept of V2G Help Electric Cars Penetrate the Auto Market?" (Michael Hidrue, Jon Lilley, Meryl P. Gardner, Willett Kempton, and George R. Parsons), Presented in Session 5.2, Environment and Sustainability Track. Academy of Marketing Science 2009 Annual Conference, May 21, 2009, Baltimore, MD.
- 2009 "Vehicle to Grid" Presentation for ISO-New England, Massachusetts, 25 Mar 2009.
- 2009 "Demonstration of MAGICC's Vehicle to Grid" PHEV Executive Summit. Jointly sponsored by PJM Interconnect and Electric Power Research Institute. 26 Jan 2009.
- 2009 "Grid Integration of Large Fluctuating Power Generation with Plug-in Vehicles" Joint CDMC/CEIC Seminar, Carnegie Mellon University, Pittsburgh, 4 Feb 2009.
- 2009 "Integrating Electric Vehicles into a Smarter Electric Grid", New England Electric Restructuring Roundtable. Boston Massachusetts. 13 Feb 2008. (Broader Scope talk at MIT Energy Club the prior evening.)
- 2009 "Most of what Analysts tell you about renewable energy is wrong." Public Lecture

at University of Colorado, Feb 19th.

2008 "Rapid Emergence of an Offshore Wind Industry in the United States" Renewable and Appropriate Energy Laboratory, UC Berkeley, 5 Nov 2008. Talk by same title, Stanford University, Stanford, CA, 6 November 2008.

2008 "Additional Value and Revenue Streams", invited presentation for "California Electric Fuel Implementation Strategies" Nov. 12th, hosted by UC Berkeley Transportation Sustainability Research Center, for Cal Energy Commission and California PUC. Berkeley, CA. Nov 12, 2008. [Kempton's presentation won the conference award for most innovative and thought-provoking]