Integration of Electric Drive Vehicles with the Electric Power Grid -- a New Value Stream

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Abstract

Battery-electric vehicles and grid-connected hybrid vehicles rely on the power grid for energy -- they have to plug in to charge their batteries. With power alerts and blackouts a recent reality in California, it is easy to conclude that the energy requirements of grid-connected electric vehicles will make the energy crisis worse. Actually, quite the opposite may be true. With a bi-directional grid power interface, virtually any vehicle that can plug into the grid can potentially provide beneficial support to the grid.

Battery electric vehicles can support the grid exceptionally well by providing any of a number of functions known collectively as ancillary services. These services are vital to the smooth and efficient operation of the power grid. A hybrid vehicle can provide ancillary services, and can also generate power. Fuel cells are already being commercialized for small stationary power sources, so a vehicle-mounted fuel cell could also serve as a vehicle-to-grid power source. Sharing power assets between transportation and power generation functions can create a compelling new economics for electrically-propelled vehicles.

Keywords: energy source, energy storage, load management, conductive charger, HEV

1. Introduction

The development of vehicle-to-grid power systems can accelerate commercialization of battery electric vehicles, hybrid vehicles, and fuel cell vehicles. This paper describes the technology of this rapidly evolving concept. A detailed economic evaluation of the vehicle-to-grid concept is provided in Kempton et.al. [1].

Most personal transportation vehicles sit parked more than 20 hours a day, during which time they represent an idle asset. Vehicles that incorporate electric propulsion can be utilized as power sources while parked because their drive systems include the fundamental elements for generating AC power. Utilizing idle vehicles to provide valuable electric power functions can produce a positive net revenue stream and create a powerful economic incentive to own an electrically-propelled vehicle.

Production of valued electric power services from electrically-propelled vehicles has been demonstrated. Performance and efficiency data are presented. The range of services is broad, and includes mobile AC power, backup power for homes or businesses, power generation during peak demand periods, and grid ancillary services such as spinning reserves, regulation, automatic generation control, reactive power, and transmission stabilization. Most of these functions already have established economic value when procured from non-vehicular sources.

The economics of vehicle-to-grid are examined. Automotive economies of scale and emission control technologies can reduce both the cost and emissions for vehicle-based distributed generation assets relative to dedicated stationary units. Furthermore, since the asset cost of the propulsion system is primarily allocated for transportation, only the incremental cost of battery wear-out and system deterioration need be covered by the vehicle-to-grid functions. Analysis suggests that in many cases, these incremental costs are well below the market value of vehicle-to-grid services resulting in a new value stream that will attract investment in vehicle-to-grid infrastructure and commerce systems [1].

A commercial vehicle-to-grid power system is envisioned. It includes compatible onboard vehicle power systems, vehicle-to-grid power infrastructure similar to that for charging electric vehicles, communications and control links between the vehicle and the power operator, and electronic commerce systems for handling micro transactions between each vehicle and the ultimate power user. Different types of electrically-propelled vehicles will provide different types of power services. Vehicles with significant energy stored in batteries could perform as uninterruptible power systems for whole houses and provide valued grid ancillary services. Hybrid vehicles with internal combustion engines and state-of-the-art emissions systems show the potential for power generation at specific emissions levels far below that of small microturbines, and in some cases better than the best new large powerplants. For hybrid or fuel cell vehicles, a connection to low pressure natural gas or hydrogen could also made at compatible parking locations to provide a continuous source of fuel.

One million electrically-propelled cars by the year 2020 could represent a huge new source of generation and storage capacity for the power grid. The value created by vehicle-to-grid capability makes a fleet of that size in 2020 economically realistic.

In the broader sense, there has been discussion of how the future power grid will evolve toward open standards, with grid access points, even down to the consumer level, used for buying and selling 'packets' of energy, much like data travels in packets on the internet [2, 3]. Grid connected vehicles will be a major player in this new open energy grid architecture.

2. Description of Value-Added functions

2.1 Grid Connected Functions

2.1.1. Spinning and Non-Spinning Reserves

Spinning reserves are contracts for generating capacity that is up and running, and is synchronized with the power line. A generating station that is operating at part capacity could sell spinning reserves for its unused capacity. When called it must ramp up to its full output within 10 minutes. The principal difference between spinning and non-spinning reserves is that the spinning reserves generator is on-line, and it contributes to grid stability helping to arrest the decay of system frequency when there is a sudden loss of another resource on the system.

2.1.2. Regulation

Grid operators must continuously fine-tune the match between power generation (and import) and power consumption. In many power markets, this function, called regulation or automatic generation control (AGC), is unbundled from power generation, and is procured as an ancillary service. Grid regulation requires a power system that can ramp power up or down under real time control of the grid operator. Regulation is used to assure that the grid operation in the grid-operator's control area complies with the performance standards required by power grid oversight agencies.[1] The measure of the quality of the grid operation in a control area is called ACE, for Area Control Error. ACE is a combination of the control area's deviation from scheduled net import (or export) of power and the

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[1] Most of California power grid is operated by the California Independent System Operator (ISO). The California ISO must comply with performance standards set by the Western States Coordinating Council (WSCC) and the National Energy Reliability Council (NERC).

control area's contribution to power variations needed to maintain the grid frequency at its target level (60 Hz in the US).

The magnitude of ACE and the power needed to keep ACE within prescribed limits is small relative to the total power consumed in the control area. In California, it is typically about 0.5%. Figure 1 shows the system load profile and the ACE for a sample day in California.

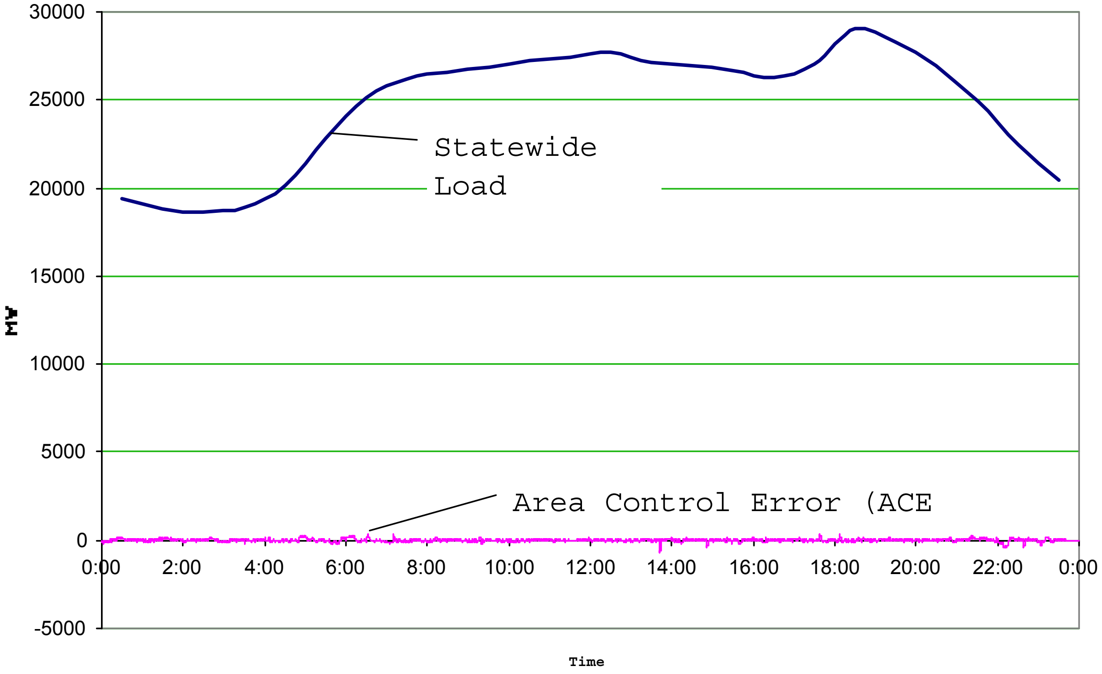

Figure 1. California Electrical Load and Area Control Error for March 14, 2001

Today in California, powerplants and hydroelectric facilities perform the regulation function. Plants providing regulation are required to be under real-time direct control of the ISO's AGC computer system. Regulation is procured by competitive bidding on day-ahead and day-of markets. Regulation is procured for each hour of the day as power capacity – not energy – that can ramp up or down from a nominal generation level.

The California ISO typically procures 1600 MW of regulation as a combination of regulation up (increasing power from nominal) and regulation down (decreasing power from nominal) every hour, and spends on the order of 1 to 3 million dollars each day on these services. Typically, regulation services represent about 80% of the total ancillary service expenditures by the ISO.

2.1.3. Peak Shaving

Peak shaving is a local application in which inside-the-meter generation is dispatched to reduce demand charges by reducing the peak electricity demand seen by the meter. The demand charge is a fee paid by non-residential electricity customers based on their peak monthly power demand.

Demand charges typically range from $5 to $15 per kW peak demand per month. Peak demand is usually based on a 15-minute running average.

2.2 Stand-Alone Functions

Stand-alone functions are those in which power is supplied independent of the grid. Examples of stand-alone applications include providing backup power for homes and businesses when the grid power is down, and providing remote AC power when away from the grid. Vehicles with these functions provide value to customers who would otherwise have to purchase separate portable or backup generators. DaimlerChrysler has announced their plans to produce a hybrid pickup truck with 20kW of stationary generation capacity, targeted to contractors for providing power at construction work sites[4]. They note that this generation will have exhaust emissions far below the uncontrolled portable generators that would otherwise have to be used.

2.3 Future Applications

Because the grid-power capability of connected electric drive vehicles will have virtually instant response, there may be entirely new potential applications beneficial to the operation of the grid. For example, some transmission lines are limited in capacity due to stability limits rather than thermal limits. New transmission capacity might be made available on these circuits if vehicles could perform active stability control services. A statewide fleet of 100,000 connected vehicles could provide 1,000 MW of geographically-dispersed power, with the potential for synchronized fast-response control. Geographic location of each vehicle (through GPS) could also be automatically included in control algorithms. In addition to providing position information for each vehicle, GPS can also be used to provied a precise time reference for the vehicles. With the approach, all vehicles could be synchronized to within about 10 microseconds.

This vehicle-based capability would represent a massive new force to deal with grid instability. It would also represent a vast new data acquisition system for monitoring grid voltage, frequency, and relative power phase. The technical challenge will be to develop suitable control algorithms, and to communicate and synchronize the power of all of the vehicles. More research is needed, but there are potentially big economic payoffs.

3. Vehicle-to-Grid applications by Vehicle Type

3.1 Electric Vehicles

Electric vehicles with energy stored in batteries could perform a variety of services while connected to the power grid. Any capacity beyond that needed for the next trip could be sold as a spinning reserve ancillary service. The contracted capacity and energy prices will determine how often the reserve is actually called. A high bid on the energy price results in a lower price for the reserve capacity and less likelihood of being called. Lower energy price bids will allow a higher capacity price at the expense of being dispatched more often. There will be an optimum that balances capacity payments, number of dispatches, and battery wear-out costs for maximum revenue.

The total amount of reserve energy that would be available from an electric vehicle on a daily basis is relatively small. Practical considerations would limit the discharge of bulk battery energy into the grid to once a day. Because of these considerations, selling of reserve capacity is not expected to have large value. However, there are other services that can be provided simulataneously: regulation and reactive power.

3.1.1. Regulation

Battery electric vehicles with bi-directional grid power capability are well-suited to providing regulation due to their ability to respond rapidly to power commands, and because the net energy requirement for regulation usually nets out to zero if the nominal generation level is set at zero . This means that the vehicle would be sourcing and sinking power under real time commands from the ISO. Over an extended time period, the net total energy balances out to approximately zero. Because of this, a battery electric vehicle could perform regulation function indefinitely without discharging the battery. The battery state of charge would be maintained at a level high-enough to afford the driver most of the available range, but not high enough to place a limit on the ability to sink power as required by the regulation AGC commands.

3.1.2. Reactive Power

The power grid also needs reactive power – current out of phase with voltage – in order to maintain the grid. The California ISO currently has no market for reactive power – each power provider is expected to provide reactive power as needed. In the future, it may be beneficial to unbundle reactive power and create a separate market for it. There may also be benefits to local generation and use of reactive power to improve the power factor of an electricity customer that must pay extra demand charges based on poor power factor.

3.2 Hybrid Vehicles

An automobile-based generating resource such as a grid-connected hybrid vehicle can generate small amounts of power that, when multiplied by just a fractional percentage of the vehicle fleet, amount to potentially valuable additions to peak power capacity, as shown below in Figure 2.

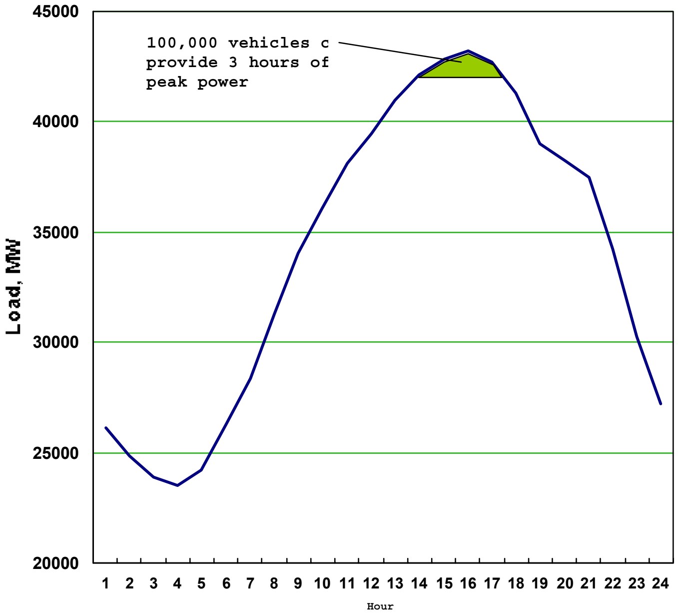

Figure 2: Example California summer peak load profile, showing how vehicles could provide power for peak demand period.

Vehicle-based generation of peak power would be clean because the engines must comply with automotive emission standards. It would be low in cost due to automotive economies of scale. While parked, automobiles are usually located where the demand is – at work sites during the day and at residences in the evening. The power they can provide will be highly available because the average automobile is idle for more than 20 hours a day. Finally, the vehicle-based generating resource will be affordable. Most of the capital costs of the power system will be assigned to its primary function as transportation. The fixed costs specific to power generation will be small.

3.3 Fuel Cell Vehicles

In the early years of fuel cell vehicle deployment, hydrogen infrastructure will be sparse, and the cost of home refueling with hydrogen derived from an electrolyzer will be 2 to 3 times more costly per mile than recharging batteries with electricity. During this period an effective fuel cell vehicle configuration may prove to be a hybrid with a relatively small range extending fuel cell. This type of vehicle will operate for a significant part of the time using grid-charged electricity, the fuel cell may only be used for 50% of the miles traveled. For 12,000 miles per year with vehicle energy consumption of 250 Wh/mi, the annual output of the fuel cell system would be 1500 kWh. For a 10 kW fuel cell, this represents a very low utilization rate, or capacity factor, of only 1.7 percent.

If the fuel cell could be put to work while the car is parked (which is typically 20 hours per day), the ownership economics of such a vehicle could be improved. The electrical output could be used to power local loads, offsetting power purchase from the utility, or be sold in the open market. In commercial settings, the power produced also has the potential to reduce demand charges. The heat by-product can have application for space heating or other low-temperature heat needs.

4. System Description

4.1 Infrastructure

4.1.1. Power

Standard electric vehicle conductive charging stations will serve as the grid connection point for vehicles performing grid services. Unlike inductive charging systems, conductive charging stations are inherently capable of bi-directional power flow. The functions needed to assure safety, such as shutdown upon loss of grid, are part of the grid-tied inverter and are located on the vehicle.

Existing level 2 charge stations are limited to 7.6 kW at 240V. The new level 3 AC conductive charging standard[2] allows much higher levels of AC power to be transferred between the vehicle and the grid. One manufacturer has designed a low cost charge station capable of transferring up to 40 kW [5].

4.1.2. Natural Gas

A vehicle-based distributed generation system would be expected to operate a few hours a day when the value of the energy generated is highest. Fuel could be gasoline, but a dual fuel system and an infrastructure for delivering low pressure natural gas to parked vehicles would enable stationary vehicles to generate electricity from natural gas. The natural gas would not be stored on the vehicle. Quick-connect fittings that have an interlock to preclude gas flow until the fitting is connected would

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[2] Revision of SAE J1772 recommended practice, approval expected August 2001

enable safe and convenient connection of the vehicle to the natural gas source. This would avoid the inconvenience and additional refueling emissions that would result from depleting the vehicle's gasoline supply during generation mode

4.1.3. Hydrogen

In order for a hydrogen-fueled vehicle to produce power for long periods of time while parked, a ready source of hydrogen will be required; on-board hydrogen storage would be too limited, and too 'precious' to consume for stationary generation. Far into the future, hydrogen may be distributed in pipes the way natural gas currently is. In the near term, it will be necessary to produce hydrogen in real-time from another fuel – most likely from natural gas. An off-board natural gas fuel processor is envisioned. Such a device does not produce pure hydrogen. Its output is called reformate, which is a gas composed mainly of hydrogen and carbon dioxide. It is not necessary to separate the hydrogen – reformate can be fed directly into the fuel cell, but it cannot be 'dead-headed' as can pure hydrogen. Instead, it must flow through the anode side of the fuel cell. The anode exhaust, which still has significant hydrogen content, is typically used in the reformer to provide needed process heat. The electrical output of the fuel cell is converted to the battery open circuit voltage, and inverted to AC by the vehicles' charging system and fed to the power grid through the recharge connector.

4.2 Aggregation

The power capability of any individual vehicle will be small; grid operators will want to contract with large groups of vehicles as a combined entity. Thus there is a need for a 'middleman' company to aggregate the capabilities of a large number of vehicles, and to provide a single point of contact for the grid operator. The aggregator company could be of many forms. It could be an automotive OEM that reaps an ongoing income stream by aggregating the vehicles it sells; it could be an established energy trading company; it could be the company that supplies the vehicle-to-grid power system, or it could be a startup company.

4.3 Metering

Measuring and keeping track of the vehicle-to-grid services rendered by each vehicle will involve tracking a large number of small transactions, and measuring and recording the response of each vehicle. Tracking the transactions for all of the vehicles will be the role of the aggregator. The actual vehicle-to-grid services must be measured at the point where the vehicle connects with the grid. This measurement could be accomplished with equipment that is either on board the vehicle or off board the vehicle on the infrastructure side. In order to keep infrastructure costs to a minimum and to allow existing infrastructure to be utilized as is for these functions, it is desirable to put all of these functions on the vehicle side.

Measurement of energy and power flow on the vehicle will require a meter on the vehicle that is certified and tamper-proof the way residential meters are today. Data from the meter that is sent to the aggregator for purposes of calculating the vehicle's contribution, and hence income, may need to be encrypted inside the sealed meter to ensure its integrity.

On the infrastructure side, vehicle connection points will all be on the customer-side of a utility meter. For some vehicle-to-grid services, it will not be necessary to take into account the effect the service has on the net energy measured by this meter. These could include regulation, in which the net energy is almost zero, or performing the services while the vehicle is at the driver's home, where the home's meter charges accrue to the same person whose vehicle is performing vehicle-to-grid services. In other cases, it will be important for the system that is tracking the transactions to know which meter the vehicle is connected through. This can be easily determined without any need for vehicle-to-infrastructure communications or infrastructure modifications. With a global positioning system (GPS) receiver in the vehicle, the vehicle's location can be matched with a database of charge station locations. The utility meter account information for each charge station can be stored in the database. Knowing where the vehicle is then provides the information on which meter the vehicle is connected through. This database function would be handled by the aggregator, not the vehicle. The vehicle would need only to report its GPS position to the aggregator.

4.4 Communication

Implementation of vehicle-to-grid services requires that the vehicle must be able to send and receive information to the aggregator. This information will include: vehicle availability, location, power/energy capacity, dispatch commands, and measured response to dispatch commands. The internet will be the road that the data travels on. There are several options for getting the vehicle connected to the internet. One approach requires bringing an internet connection to the infrastructure-side connection point, and then making the connection to the vehicle either over a wired connection in the power coupler, or through a wireless connection such as IRDA or Bluetooth. This approach has the disadvantage of adding complexity on the infrastructure side, and would require special vehicle charging stations for vehicle-to-grid functionality. This would hamper or even prevent the early growth and deployment of vehicle-to-grid. A better solution is to keep all needed communications capabilities on the vehicle side, so that existing electric vehicle infrastructure can be used for vehicle-to-grid without modifications.

Mobile-based wireless communications are evolving rapidly, and there are several off-the-shelf systems available and deployed, including bi-directional paging, cellular packet data protocol (CPDP), NTT DoCoMo i-mode, and general packet radio service or GPRS. Vehicle-based wireless communication also opens up a wide variety of vehicle telematics applications, and makes possible remote diagnostics of vehicle problems.

4.5 System Operation

Operation of a vehicle-to-grid system involves four major stakeholder groups: vehicle drivers, the aggregator, buyer of the aggregated vehicle services, and the owners of the interconnect points and their associated metered utility accounts. A fundamental principal in vehicle-to-grid is to always be sure to take care of the driver's transportation needs as the highest priority. Drivers don't want any surprises when they get into their vehicle. Driver's would communicate their driving needs to the aggregator through a vehicle based control panel, and/or a personalized web page hosted by the aggregator. The driver information would include a default weekly profile of expected vehicle usage, and desired range reserves at times of non-planned use. Exceptions to the default profile could be entered at any time as a one-time change (such as needing the vehicle during the middle of the day with a full charge). Expected vehicle usage profiles would always be stored in the vehicle as well as with the aggregator.

The aggregator would consolidate all of the default profiles of the aggregated vehicles to create a default profile of the aggregated 'virtual power plant'. This profile shows how many vehicles are expected to be on-line at any given time of day, and what energy and power capacity is expected to be available. This information would be used to negotiate contracts for power services from these vehicles. These contracts could be based on any lead time or duration –they could be annual contracts, day ahead contracts for a certain hour, or real time.

In real time, vehicles would 'sign-in' with the aggregator when they were initially connected to the grid after driving. The information would include an identity, GPS location, battery state of charge, and power capacity of the interconnect. This real time actual data would be used to update the expected availability based on default profiles and planned deviations. Power services would be dispatched to vehicles by the aggregator as needed. Some services, such as regulation, would be dispatched uniformly to all vehicles in the control area. Other services may be dispatched only to vehicles within a specific geographical region. Services such as regulation would require a continuous stream of commands (typically with 4 second updates). Vehicles would respond to dispatch commands with power flow to or from the grid. Algorithms within each vehicle would in some cases limit or stop the requested dispatch of services in order to maintain the vehicle in a state of charge condition that meets the driver's most recent required usage profile.

Energy services are typically purchased for delivery over an hour period. Drivers of vehicles generally do not have driving requirements that line up on hourly boundaries. It would be very inconvenient to the driver to be required to remain connected when they need to drive their vehicle. As envisioned, the system would not place any restrictions on when drivers could disconnect from the grid. With a large number of vehicles, the total capacity available at any given time will be highly predictable despite the large variability of individual vehicle availability. Some vehicles would be off-line when they were planned to be on-line, and vice-versa, but the overall impact on total available capacity is expected to be small.

5. Test Results

5.1 Regulation with a Battery Electric Vehicle

Tests have been made to evaluate the feasibility of performing regulation services with battery electric vehicles. AC Propulsion's second generation AC150 drive train with integrated bi-directional 20-kW grid power interface [6] was installed in a test car. The power flow to or from the vehicle was controlled by an external laptop computer.

Initial tests were to implement a typical generator 'droop curve' in which the vehicle power output varies in proportion to the deviation of the grid frequency from 60 Hz. Grid frequency is already measured by the vehicle drivetrain as part of the loss-of-grid safety shut down system . Figure 3 shows a screen from the laptop computer, showing on top a display of the frequency error, and on the bottom, the actual vehicle power response (shown here in AC line current units at 208V). The vehicle and it's batttery had no problems operating in this mode as long as the frequency didn't deviate to one side of 60 Hz for a long period. Longer deviations resulted in greater than desired excursions in the battery state of charge. Software controls were implemented to add a feedback element to apply a long-time-constant correction to keep the battery pack closer to a constant state of charge.

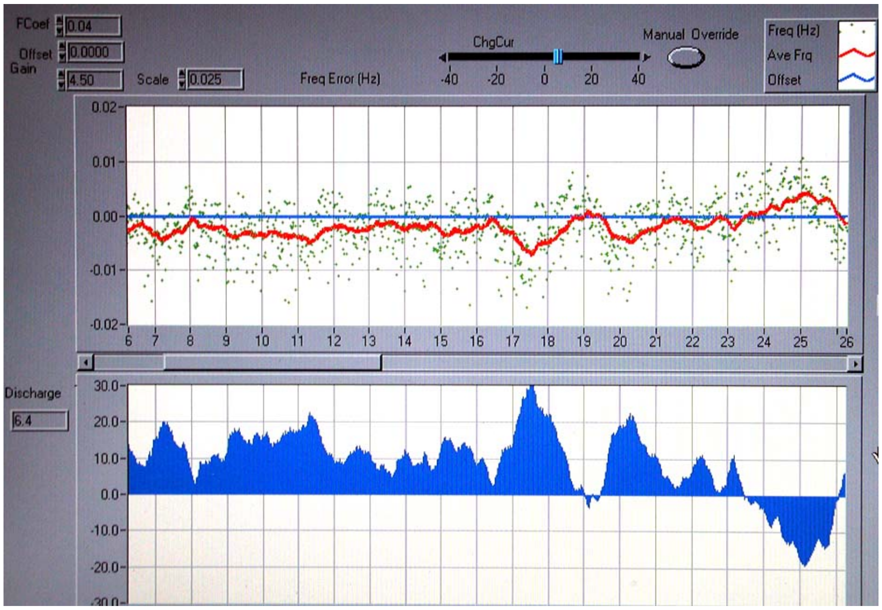
FCoef 0.04
Offset 0.0000
Gain 4.50
Scale 0.025
Discharge 6.4

Figure 3: Example of vehicle power response to grid frequency error. Top line is frequency error (deviation from 60 Hz,. Bottom trace is AC line current (at 208V).

While there may be some benefit to having vehicles add more ‘droop curve capacity’ to the grid to reduce frequency variations, there is currently not any market for such a service. The existing market for regulation services requires real-time control of power level by the grid operator’s automatic generation control (AGC) computer system. The AGC system in effect runs a feedback loop that attempts to zero out the Area Control Error (ACE). In order to test vehicles on a sample AGC command profile, the California ISO provided one day of historical ACE data. Vehicle testing was performed by ‘playing back’ this data in real time to the vehicle’s bi-directional grid interface. To convert from statewide ACE to a vehicle command, a simple proportional gain control loop was assumed. Testing is still underway, and detailed quantitative results are not yet available. Qualitatively, there were no problems with batteries overheating when the profile was run through the workday.

Figure 4 shows the expected power and energy response of a vehicle operating in regulation mode with a gain of -0.05 kW per MW ACE (ie. the vehicle absorbs .05 kW for every MW of ACE, or if ACE is –100 MW, the vehicle feeds 5 kW to the grid). Power is clipped at 7.68 kW to reflect the power limits of existing Level 2 charging stations. Note that the battery energy deviates only plus or minus about 2 kWh, an acceptable amount for full function electric vehicles. Figure 5 shows a detailed trace of power and energy for a one-hour period. Note that the power deviations typically occur over many minutes – much slower than drive cycles, which have power deviations over a few seconds.

A typical operating scenario for a full function electric vehicle that is used for commuting and for grid regulation is shown in Figure 6. It is assumed that there is a recharge connection point available at home and at work. The two commuting periods are each about 25 minutes and 16 miles. When the driver gets to work, the car is plugged in to the grid and grid regulation and recharge to a target of 80 percent state of charge are initiated. The recharge is complete after about an hour, and the vehicle continues to provide regulation until the driver leaves to go home. Upon arrival at home, the vehicle is plugged in to the grid again and regulation resumes. At 9:00 pm, when off peak electricity rates are in effect, a gradual battery recharge is superimposed on top of the regulation function. The recharge power offset can be very small – just enough to bring the battery capacity back up to about 80 percent in time for the morning commute. The vehicle is now in use 24 hours a day: one hour for transportation, and 23 hours for revenue generation.

The added use of the battery will of course cause it to wear out more quickly, as measured in calendar time or miles traveled. This is exactly what this concept is intended to do. The wear-out of the battery generates revenue sufficient to cover the cost of necessary battery replacements for the life of the vehicle. The cost of using the battery for transportation is covered by the revenue generated, creating a real and substantial economic benefit for the vehicle owner.

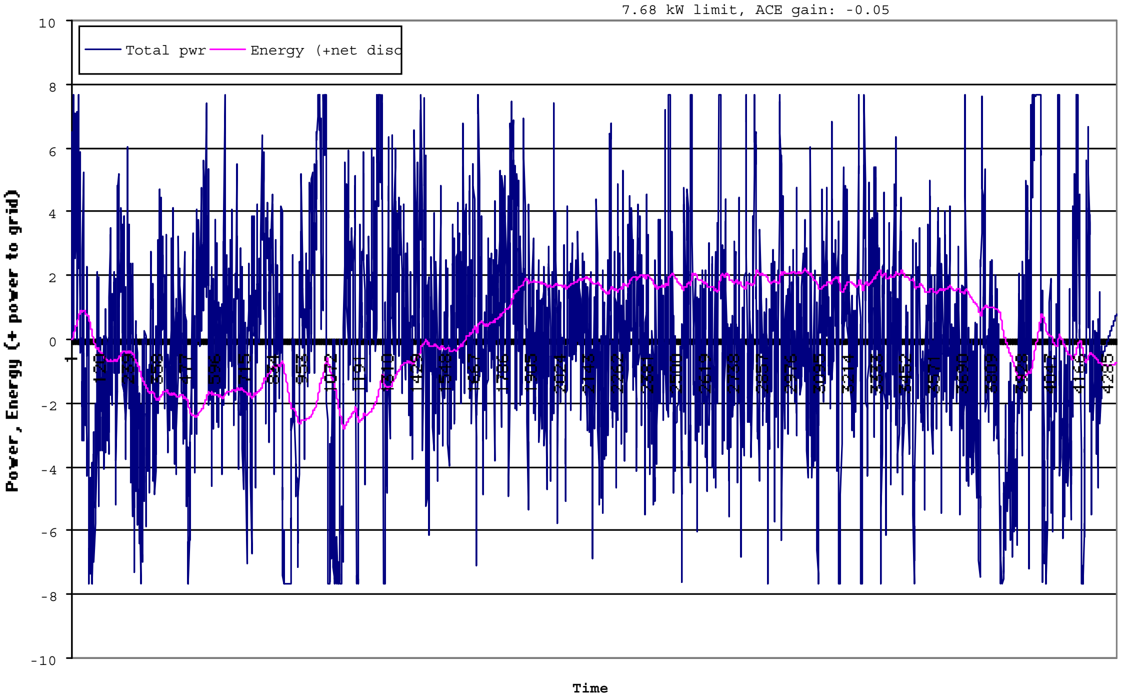

Figure 4: Power and energy profile for a vehicle performing grid regulation continuously over 24 hours

In the example shown, the daily throughput energy of the battery is dominated by the regulation function, not the driving. Regulation is responsible for 27 kWh of throughput energy, and driving about 8 kWh. It is expected that the shallow cycling and low power levels in performing regulation will cause relatively less battery wear-out than driving does. Further testing is needed. An additional consideration is that batteries usually have a calendar life wear out mechanism in addition to a cycle life wear out mechanism. Many efficient electric vehicles driven typical daily distances may experience calendar life wear-out long before cycle life becomes a problem. In this case, finding an other way to ‘use up’ the battery before the calendar uses it up comes with little or no incremental cost.

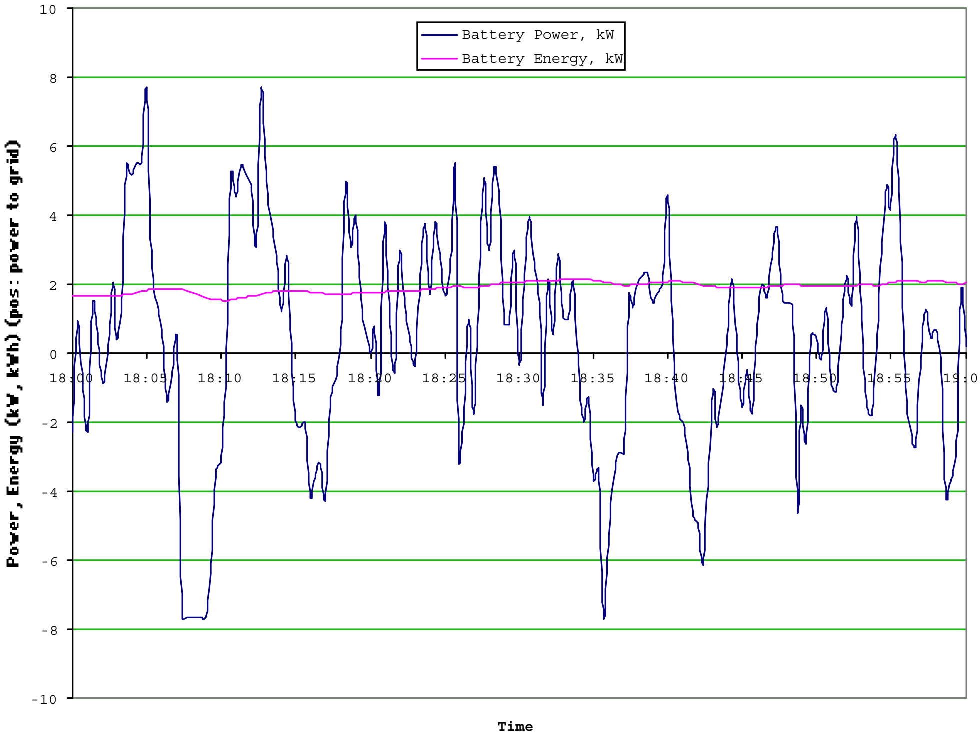

Figure 5: Power and energy profile for one hour (18:00 to 19:00)

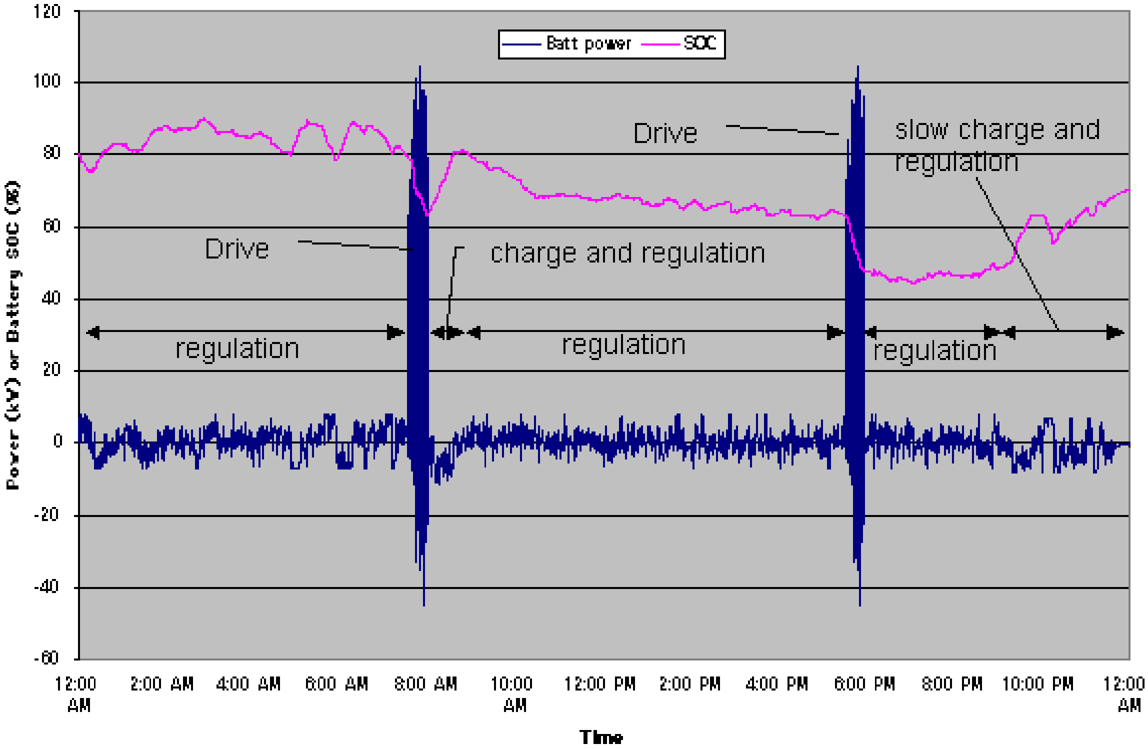

Figure 6: Example of EV used for commuting and grid regulation.

5.2 Generation from a Hybrid Electric Vehicle

Modern automotive emissions systems promise the potential for superior emissions performance compared to other forms of distributed generation. The Super Ultra Low Emissions Vehicle (SULEV) Toyota Prius may be especially well suited to this task. Automotive emissions are measured over prescribed driving cycles and are expressed on a per-mile basis. A test was run at the CARB emissions laboratory in El Monte on February 21, 2001 to measure Prius emissions when operated in a constant power operating mode (Figure 7)

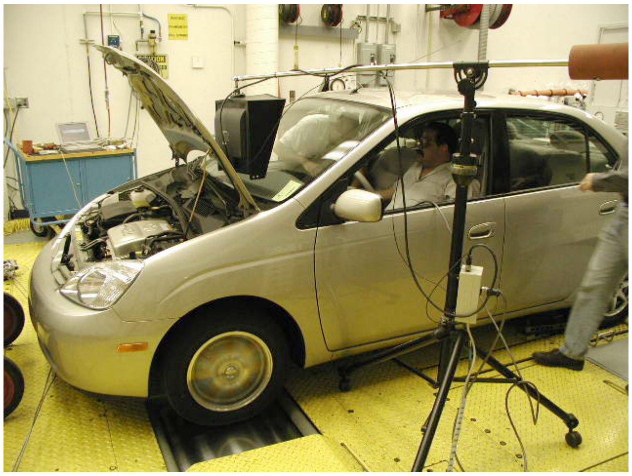

Figure 7. Prius emissions testing at constant output

Emissions were measured at three power points that are representative of the power levels that could be sustained continuously, subject cooling capacity while stationary. Load was provided by a single-roll dynamometer powered by the vehicle's front wheels. The dynamometer was programmed with a load curve which provided for 9.1 kW of power absorbed by the roll at 96.5 kph (60 mph). Tests were run at speeds approximating 8, 10, and 14 kW. At each test point, a bag sample was taken for 100 seconds, and post processed through an emissions analyzer to determine the mass of criteria pollutants. A background sample was taken simultaneously. Three consecutive tests were run at the 10 kW point, one at the 8 kW point, and two at the 14 kW point (although the second bag at this power point was not processed properly and is not included in the results). The raw results listed the net mass of HC, NMHC, CO, CO2, and NOx for the 100-second sample. Table 1 lists the results, expressed in g/MWh and in lb/MWh. Also shown is emissions data for a modern combined-cycle powerplant[7], and for the Capstone 28 kW microturbine [8]. Note that the Prius NOx emissions are lower than the combined cycle power plant.

Table 1. Prius Emissions at Constant Power

Power absorbed by dyanmometer roll, kW	**NMHC, g/MWh, (lb/MWh)**	**CO, g/MWh, (lb/MWh)**	**NOX, g/MWh, (lb/MWh)**
8.103	0[3]	630., (1.39)	0[4]
9.998	39., (0.087)[5]	639., (1.41)[6]	3.6, (0.008)[7]
14.284	5.0, (0.011)	680., (1.50)	0[8]
Combined Cycle powerplant	50., (0.11)	77., (0.17)	59.0, (0.13)
Capstone turbine	77, (0.171)[9]	603., (1.33)	223, (0.491)

Fuel consumption was also measured. From this data it is possible to calculate the efficiency and heat rate. For this calculation, an estimate of the power loss of the tires on the dynamometer roll was added to the power absorbed by the roll. Table 2 lists the results with comparisons to other forms of DG systems.

Table 2. Prius Efficiency at Constant Power

	Power absorbed by dynamometer roll, kW	Total power, including rolling resis loss, kW	Efficiency[10]	Heat Rate, MJ/kWh, (BTU/kWh)
Prius	8.103	9.727	25.2	14.3, (13,575)
	9.998	11.745	27.7	13.0 (12,343)
	14.284	16.258	28.6	12.6, (11,946)
Capstone Turbine				15.9, (15,100)
Plug Power fuel cell				13.8, (13,070)

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[3] Sample less than background

[4] Sample less than background

[5] First bag only; bags 2 and 3 had sample less than background

[6] Average of three bags

[7] First bag only; bags 2 and 3 reported zero net emissions

[8] Sample lower than background

[9] Total HC (NMHC not available)

[10] based on 115,000 BTU/gallon

6. Conclusions

There is a real potential for electric drive vehicles to create value while they are stationary and plugged in to the power grid. By deploying the vehicle's power systems to perform ancillary services for the power grid operator, there is the potential for economic value to be created. With the value created through vehicle-based grid services, partially offsetting purchase and operating costs, electric drive vehicles may have a lower net ownership costs than conventional vehicles. This would invert the cost vs. emissions benefit tradeoff; there could be a cost benefit together with the emissions benefit. Vehicle based grid services may prove to be instrumental in overcoming market and cost barriers in the adoption of electric and other advanced technology vehicles.

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