

PG&E and Tesla Motors: Vehicle to Grid Demonstration and Evaluation Program

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Abstract

Pacific Gas & Electric Company (PG&E) and Tesla Motors have established a joint program to evaluate vehicle-to-grid applications of plug-in vehicles. This paper discusses vehicle-to-grid applications and benefits including the various forms of ancillary services with a focus on smart charging as a means to supply the grid regulation ancillary service.

The paper addresses diverse technical issues such as the ability of a unidirectional charger to supply regulation services up and down, communication and control methods among the vehicle, vehicle owner/operator, the utility and advanced electrical meter. The paper closes with suggestions for future demonstrations and pilot programs that will assist in further defining the technical requirements.

Keywords: “plug-in vehicles”, “vehicle to grid”, “V2G”, “smart charging”, “grid regulation”

1. Introduction

Vehicles that plug in to the power grid for some or all of their energy needs have the potential to make valuable contributions to the production, transmission, and distribution of electric power. Plug-in vehicles, both battery electric and plug-in hybrids, due to price signals from time of use electrical rates will be primarily charged at night when there is ample generation capacity [1]. By increasing overall electricity consumption without any significant increase in the electricity infrastructure, fixed costs will be spread over a wider base, reducing electricity costs to all ratepayers [2]. Plug-in vehicles will also be a new resource to assist with grid operations. Specifically, the energy storage capacity of a plug-in vehicle can be a storage resource for the grid, and vehicle charging rates (quantity and timing) can be controlled remotely by the utilities, aggregator or a grid operator to perform ancillary services for the grid. Further, since the plug-in vehicles' load can be remotely dispatched to provide prompt response to the expected more frequent regulation needs of high levels of intermittent resources, the penetration of intermittent

renewable resources such as wind energy have the potential to grow beyond the level that would have been practical without plug-in vehicles. In the future, the current grid model of dispatching generation to match load can be changed for a growing fraction of the total load: load that can be dispatched to match generation. Plug-in vehicles will have this capability and may be a key enabler to a cleaner, more renewable, and lower-carbon grid.

2. Background

The recent surge in interest in vehicles that can plug in to the grid for some or all of their energy needs has been driven by:

- Exhaust emission effects on local air quality
- A desire to diversify energy sources for transportation (with the associated benefit of reducing dependence on foreign oil)
- Global climate change
- Fueling convenience and reduced fuel cost

Plug-in vehicles can make significant contributions in all of these areas. Further, with recent advances in communication technologies, utilities such as Pacific Gas and Electric Company (PG&E) have realized that plug-in vehicles need not be just another load on the electrical grid; rather that these plug-in vehicles have the potential to provide valuable support to the electrical grid in ways not recognized until recently.

3. Vehicle to Grid Technology

Plug-in vehicles have a battery pack (energy storage device) and a charger. The charger takes in alternating current (AC) power from the grid and converts it to direct current (DC) to charge the battery pack. In some vehicles, the charger will be bidirectional; able to deliver power back to the grid from the vehicle's battery as well as charge the battery. The typical daily energy requirement of plug in vehicles will be modest (on the order of 5 to 40 kWh), compared to the power capacity of the vehicle's battery charger, which will range typically from 2kW to 17kW. With the typical charger ratings, the battery recharge times will be only a few hours. Since most vehicles are generally in use only a couple of hours per day, there is a great deal of flexibility as to the timing and power profile of how and when vehicles are recharged. Simply using lower-cost off-peak electricity is one example, but there is much more potential.

Vehicles with remotely-controlled battery chargers can provide services to support grid operation. Vehicles with bi-directional chargers can cycle power to and from the grid under remote control, even while charging. Vehicles with unidirectional chargers (i.e. they cannot feed power back to the grid), can still provide services to the grid by allowing the remote control of the battery charging rate. These concepts of vehicles providing services to the grid are collectively referred to as "vehicle to grid" or V2G. Note that V2G does not necessarily mean that power has to flow from the vehicle to the grid; vehicles with unidirectional chargers that are controlled to provide a service to the grid are also providing a "vehicle to grid" service. The services vehicles provide to the grid have value that may result in payments back to vehicle drivers resulting in lower vehicle operating costs.

3.1 Background

Electrical grid operation requires assuring in real time that the total generation matches the total load. If there is a mismatch between generation and load, the frequency of the grid will deviate from the standard of 60 Hertz. The power grid in the United States is composed of three main regions: Western, Eastern, and Texas. Within a region, the power grid is interconnected with AC transmission lines. Regions are further subdivided into control areas. Each control area has a grid operator that manages the electrical generation in their area and interchanges of electricity with other control areas. The grid operator schedules generation in advance to match up with expected loads, and then in real time fine-tunes the level of generation to match load and scheduled interchanges with other control areas.

3.2 Ancillary Services

Grid operators use a variety of tools to keep the grid operating smoothly. These tools are commonly referred to as “ancillary services”. Some examples of ancillary services are spinning reserves, non-spinning reserves, and regulation. Many grid operators, including the California Independent System Operator, (or CAISO), maintain markets for ancillary services. In California, powerplant operators submit bids for ancillary services on day-ahead and hour-ahead markets. Bids typically include the hour the service will be offered, the amount or capacity of the service offered, and the offered price for providing the service. The CAISO evaluates all the bids and determines a market-clearing-price for each ancillary service each hour. The market clearing price is the price point at which the requisite total capacity of that particular ancillary service has bid at or below. Each winning bidder is paid the market clearing price for providing the service.

Previous studies [3,4] have identified regulation as the most valuable ancillary service that vehicles could provide. Regulation is a service that gives the grid operator the ability to directly control the output of a powerplant up and down in real time (at 4 second update rates typically). Regulation is used to fine-tune the match between generation, load, and interchange with other control areas and to contribute to overall grid frequency control.

The CAISO divides regulation into two parts: regulation up and regulation down. Regulation up represents increasing a powerplant’s output from a nominal level and regulation down represents decreasing a powerplant’s output from a nominal level. Powerplants that provide regulation services will have a nominal scheduled power output level, often referred to as the preferred operating point, or POP, and a regulation up limit, and a regulation down limit. The POP, regulation up limit, regulation down limits are contracted by the hour; these values are fixed to specific levels for one hour at a time. Figure 1 below shows an example of a powerplant that is providing regulation up and regulation down¹, showing the POP, up and down limits, and the actual dispatched power level. The market value of regulation is based on the up and down limits, not the actual dispatched power profile. The energy generated by the powerplant on regulation is the area under the actual dispatched power curve.

¹ Powerplants that are providing regulation are referred to as being under AGC (for automatic generation control)

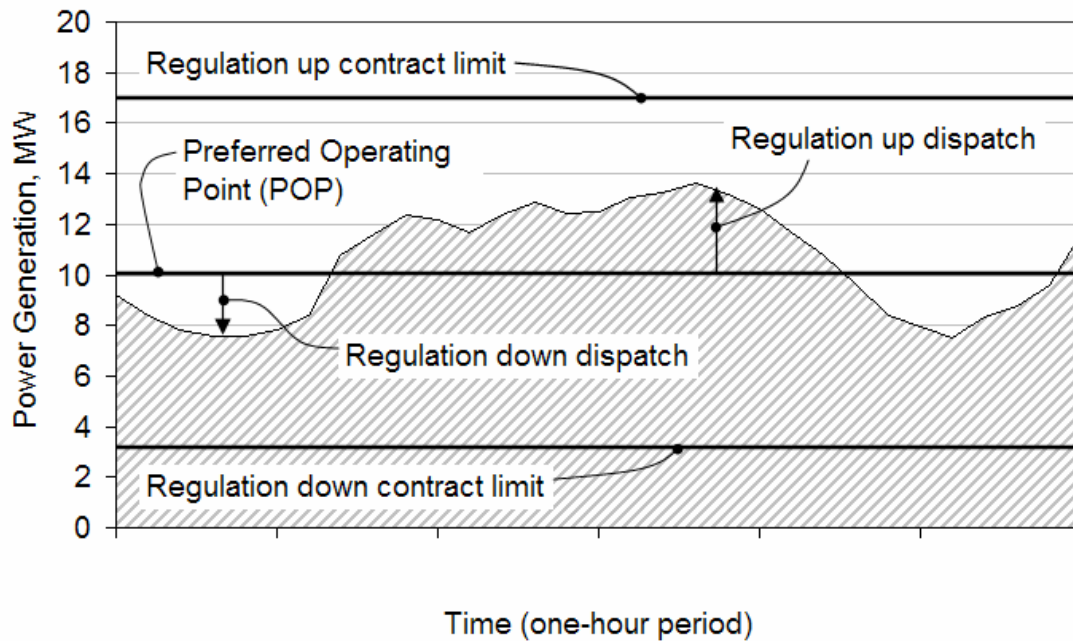


Figure 1. Example power profile for a power generator providing regulation up and regulation down. The shaded area represents the energy generated over the one-hour period.

The power fluctuations due to dispatch of regulation in the power profile shown in Figure 1 could equally well come from plug-in vehicles whose charger power levels are controlled by a utility, aggregator, or the grid operator. The only difference is the value of the POP. For a powerplant, the POP is a positive value (i.e. a nominal generation level). For a plug in vehicle, the POP could be zero, or it could be negative. That is, the regulation service does not directly depend on the value of the POP; regulation is the capability to deviate up or down from a particular POP value. Hence the POP can just as easily be negative (a load) as positive (generation).

Figures 2a and 2b show two examples of vehicles providing regulation. Figure 2a illustrates a vehicle providing regulation with a POP value of zero. This vehicle has a bi-directional battery charger and is providing power to the grid for regulation up and taking power from the grid for regulation down. Figure 2b illustrates a vehicle with a unidirectional 14kW charger providing regulation with a -7 kW POP value. The vehicle is drawing power from the grid a nominal “POP” rate of -7 kW and providing 7 kW of regulation up and 7 kW of regulation down. At the regulation up limit, the vehicle is placing no load on the grid and at the regulation down limit, the vehicle is placing a 14 kW load on the grid.

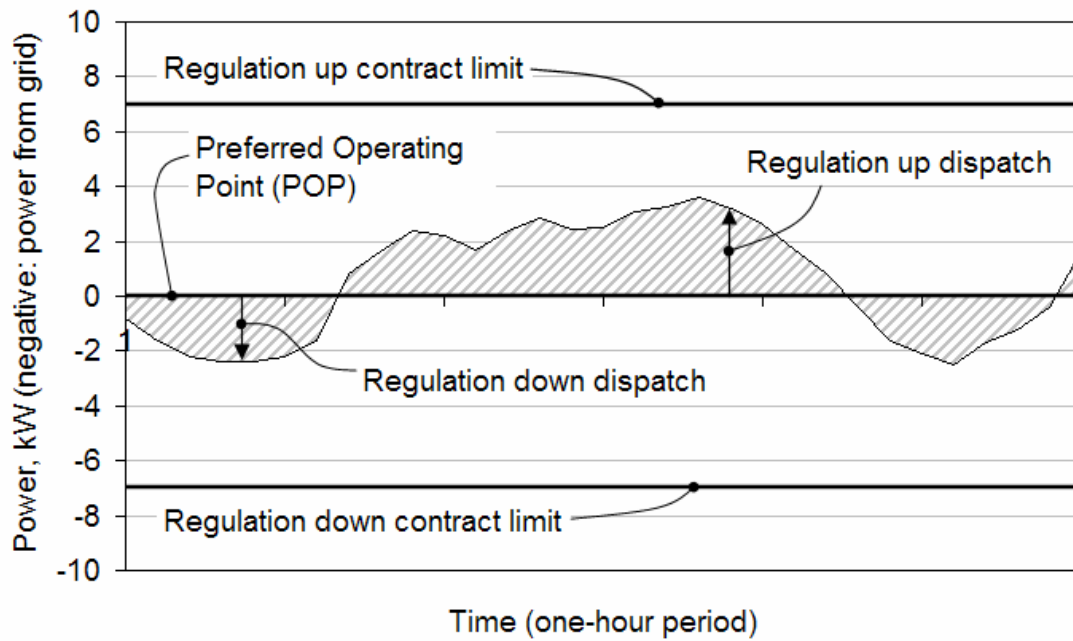


Figure 2a. Example power profiles for plug-in vehicles with a bi-directional charger providing regulation up and down ancillary service with a zero POP. The shaded area above zero represents energy delivered to the grid from the vehicle.

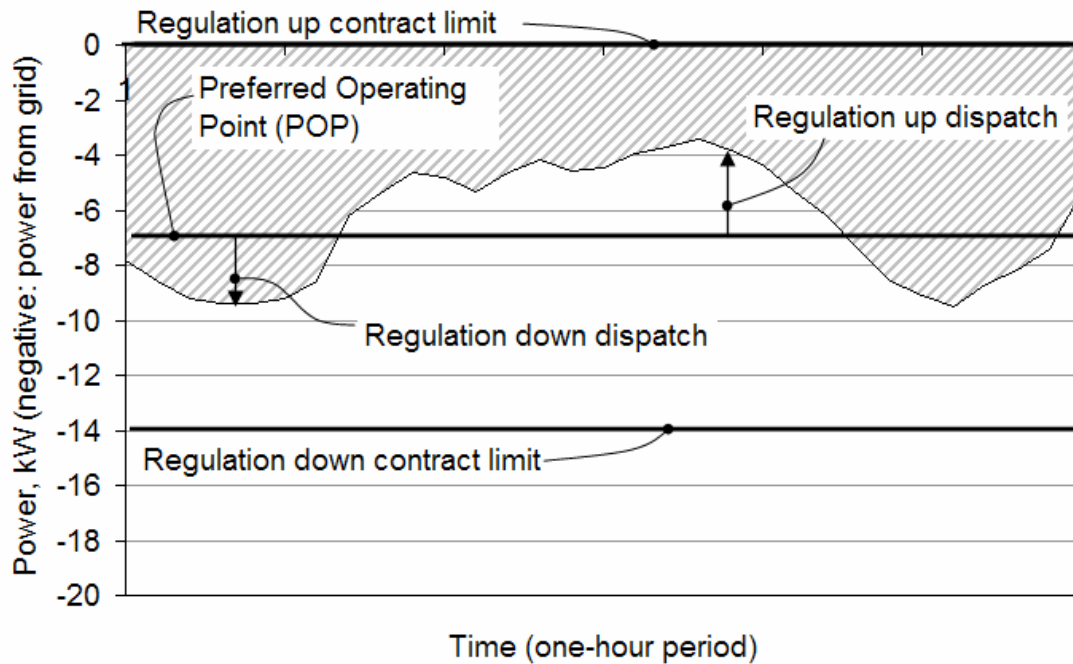


Figure 2b. Example power profiles for a plug-in vehicles with unidirectional chargers providing regulation up and down ancillary service with a POP value of -7kW (ie. 7 kW of load). The shaded area represents the energy delivered to the vehicle by the grid over the one-hour period.

The shaded area between the power profile and the axis at zero power represents the energy drawn from the grid for that period of time. The ratio of the energy drawn from the grid to the regulation capacity sold is an important metric. It represents the effective average charging rate as a fraction of the charger's maximum rated power. A low value of this ratio means that the average charging power is low, but the number of hours of regulation that can be sold is high. Initial indications are that this ratio may be on the order of 20% for regulation down. Therefore, to have a total charge energy drawn from the grid of, for example 20 kWh with a 10 kW charger, the average charging power while performing regulation down would be only 2 kW and it would take 10 hours to charge the full 20 kWh. This low charging rate is not a disadvantage with nighttime charging; rather it is an advantage, allowing for 10 hours of 10kW regulation service to be provided with only 20 kWh of total energy throughput.

At present, grid ancillary services are not provided by loads, but as illustrated above, loads appear to be capable of providing regulation just as effectively as powerplants which currently supply this service. This was acknowledged this year by the Federal Energy Regulatory Commission (FERC) which formally recognized that loads should have equal standing as powerplants in providing ancillary services. In commenting on FERC order 890 in April 2007, FERC commissioner Jon Wellinghoff stated:

“... the reforms we make to the pro forma OATT today put demand resources, for the first time, on an equal footing with other resources in directly contributing to the reliability and efficient operation and expansion of the electric transmission system. It provides that demand resources, distributed generation, and other non-generation resources capable of providing the service may provide the ancillary services Reactive Supply and Voltage Control, Regulation and Frequency Response, Energy Imbalances, Spinning Reserves, Supplemental Reserves, and Generator Imbalances.”

Potentially, plug in vehicles might even be able to do a better job than powerplants. For example, powerplants have limitations on how fast they can change power levels and plug in vehicles can change power levels virtually instantaneously.

3.3 Load-only Vehicle-to-Grid

An initial approach to implementing V2G is to focus on regulation services that can be performed with the plug-in vehicle operating as a grid-controlled load (as in Figure 2b), rather than as a system capable of feeding power back to the grid. This approach has many advantages for the initial roll out of V2G.

First, it eliminates the interconnect issues around feeding power back to the grid. It is technically feasible to make a safe and certified bi-directional charger with anti-islanding and other safety features that are found in small distributed generation systems. However, state laws and some individual utility company policies may currently preclude reverse power flow from anything but solar and wind energy systems.

Second, battery wear due to bi-directional power cycling is not well understood, and could have a cost impact greater than the benefit produced. More research is needed to quantify this aspect. Bi-directional V2G implementation will require resolution of who is responsible for potential battery wear costs.

Third, storing energy in a battery and then discharging it back into the grid results in energy losses due to the conversion of AC to DC in the charger, throughput losses in the battery, and

then DC from the battery back to AC. The energy cost needed to make up for the energy losses offsets a portion of the value created.

Plug-in vehicles need to take energy from the grid to charge batteries. It does not matter whether the energy is taken at a constant power level, or at a power level that varies over time. By charging with a power profile that provides an ancillary service to the grid, plug-in vehicles have the ability to create value while they are charging. This value can offset some of the electricity cost from charging.

4. Demonstration Project

PG&E and Tesla are collaborating on a project to develop and demonstrate a plug-in vehicle with unidirectional load-only V2G capability. The project entails a number of tasks and is ongoing. The project is briefly described in the following sections.

4.1 Evaluate Regulation Market Pricing & Dispatch Data for Potential Value

Tesla and PG&E will either obtain historical data or use real-time data on regulation procurement (quantity procured and price) and actual dispatched regulation profiles. This data will be incorporated into a valuation model to predict the value of load-only V2G services for plug-in vehicle charging. Data of interest will include the market pricing trends based on time of day and time of year, and variability of the value created.

4.1.1 Regulation Down Valuation Example

The market prices of grid ancillary services for a single day are shown in this example to illustrate how the value of vehicle-based regulation services can be determined. The market clearing price for ancillary services procured in the day-ahead market in California for August 19, 2007 is shown in Figure 3.

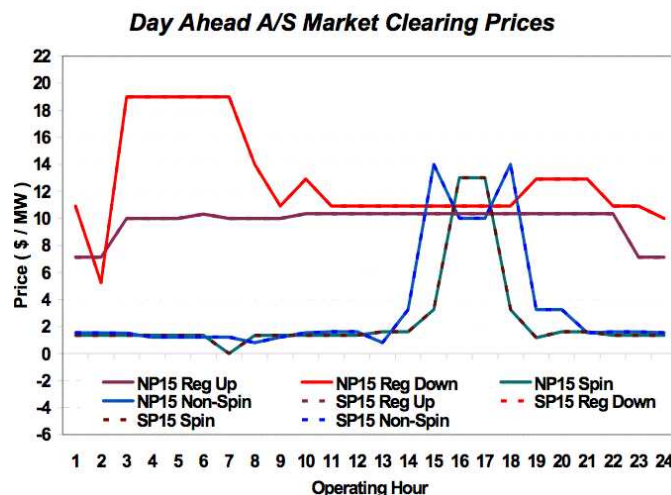


Figure 3. Day ahead ancillary services market clearing prices for August 19, 2007.

The price of ancillary services is quoted in dollars per megawatt of capacity provided, over a one-hour period. On this day, regulation down (NP15² Reg Down) was the most valuable ancillary service, with a price of \$18.99/MW for the hours ending 04 through 07 (i.e. the period beginning at 2:00 am and ending at 7:00 am ~5 hours total). The Tesla Roadster's battery charger is rated at 70 Amps and 240Volts (16.8 kW or 0.0168 MW) and the Roadster has a 53kWh battery pack which gives the vehicle more than 200 miles range. If the dispatch ratio described above is 20 percent, the Tesla Roadster would draw on average $0.2 * 16.8 \text{ kW} = 3.36 \text{ kW}$ of charging power, or 16.8 kWh of total energy over the 5 hour period. Assuming that the Roadster battery had capacity for the 16.8 kWh of energy (which would depend on the battery state of charge at the beginning), the value of the ancillary service provided would be $\$18.99/\text{MW} / \text{hour} * 0.0168 \text{ MW} * 5 \text{ hours} = \1.60 . The amount of energy transferred from the grid over the 5 hours is 16.8 kWh, so the value created per kWh of energy transferred is $\$1.60/16.8 \text{ kWh} = \$0.095/\text{kWh}$. Note this does not include any transaction/ communication costs or fees between the vehicle, and the utility, aggregator or grid operator. Analysis of a much longer time period and of the hour-ahead market will be required to determine long-term average valuations.

4.2 Develop Regulation Dispatch Algorithm

PG&E will obtain access to real time regulation AGC signals from the Cal ISO for use to create the vehicle dispatch commands. The demonstration project will initially use only one vehicle. The power level of one vehicle is too small to actually participate in the existing ancillary services market (which requires a minimum of 1 MW), so the dispatch command will necessarily not be an actual AGC command calculated for the vehicle from the CA ISO AGC system. Instead it may be a scaled version of a command to a powerplant that is performing regulation, or scaled from the total dispatch of regulation in the state.

4.3 Develop Means to Communicate with Vehicle

To demonstrate remote dispatch of the vehicle charger power level, the vehicle will be equipped with a means to communicate with it over the internet. Standard off the shelf communications hardware will be used for this project. Subsequent V2G demonstration projects may evolve to a system compatible with smart metering systems that will be deployed by utilities in the next few years.

4.4 Demonstrate Regulation-Down Ancillary Service with Tesla Electric Vehicle

The dispatch command will be sent to the vehicle at the standard 4-second interval. The vehicle will respond to each dispatch command by setting the grid power to the commanded value and sending a message back indicating the actual measured power level. Data will be collected on the accuracy of the response to the command, data latency and other factors.

5. Future Applications

5.1 Expand Demonstration to Customer Vehicles

Once the one-vehicle demonstration project is completed and the data analyzed, the next phase may involve deployment into a small group of customer-purchased Tesla Roadsters. An effort

² NP15 refers to the region of California that is north of Path 15, a major transmission line.

will be made to find a means to compensate the participants for the services provided, possibly through rebates or experimental V2G tariffs.

6. Additional Information on PG&E and Tesla Motors

6.1 Pacific Gas and Electric Company

PG&E is the primary gas and electric utility in Northern and Central California, serving 15 million customers. In addition to partnering with Tesla on V2G research, PG&E is working with the auto manufacturer to support the installation of Tesla Motors' charging stations into their customers' homes or businesses. PG&E is working with Tesla Motors to ensure proper connection in its customers' homes within the utility's northern and central California service territory and advising the auto manufacturer on its collaboration with utilities nationwide.

PG&E became the first utility in the nation to publicly demonstrate the possibility of electric vehicles to supply homes and business with electricity at a Silicon Valley Leadership Group event in April 2007. More recently, PG&E shared this technical expertise with Google in June 2007 to upgrade a company-owned Toyota Prius Plug-in Hybrid Electric Vehicle (PHEV) to be V2G capable for a demonstration at the search leader's Mountain View campus.

PG&E's PHEV/dedicated electric vehicle and V2G program is part of its broader strategy to develop innovative energy solutions that deliver the cleanest and most reliable power to its customers. In addition to its PHEV and dedicated electric vehicles, PG&E owns and operates a clean fuel fleet of fuel cell vehicles and more than 1,300 natural gas vehicles – the largest of its kind in the United States. PG&E's clean fuel fleet consists of service and crew trucks, meter reader vehicles and pool cars that run either entirely on compressed natural gas or have bi-fuel capabilities. Over the last 15 years, PG&E's clean fuel fleet has displaced over 3.4 million gallons of gasoline and diesel, and helped to avoid 6,000 tons of carbon dioxide from entering the atmosphere. For more information about Pacific Gas and Electric Company, please visit the company's web site at www.pge.com

6.2 Tesla Motors

Tesla Motors develops and manufactures vehicles that exemplify “Design, Performance, and Efficiency” while conforming to all U.S. safety, environmental, and durability standards. Tesla Motors' first offering, the Tesla Roadster, is a stylish, high-performance, 100% electric sports car, that accelerates to 60 mph in about 4 seconds and has a range of more than 200 miles on a single charge. For more information, visit www.teslamotors.com

7. References

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8. Authors



Alec N. Brooks, Director of Vehicle Technologies, Tesla Motors. Alec Brooks has been involved with electric and hybrid vehicles for more than 20 years in the areas of technology, public policy, and as a driver. At AeroVironment he led the development of the GM SunRaycer solar racing car in 1987, and later led the development of the GM Impact electric vehicle, the forerunner of the EV1. At AC Propulsion, he spearheaded the development of concepts by which connected vehicles would supply grid ancillary service functions for the benefit of the power grid and to create value for the vehicle owner. He has a Bachelor of Science degree from the University of California, Berkeley, and Masters and Ph.D degrees from Caltech, all in Civil Engineering.



Sven H. Thesen, Supervisor in PG&E's Clean Air Transportation Department. Mr. Thesen has a seventeen year career in the environmental field, holding various environmental positions in industry and consulting. His particular interest in electric transportation stems from the realization of their environmental and societal benefits. Mr. Thesen has Bachelor of Science degree in Chemical Engineering from North Carolina State University. Besides his lovely wife and two children, his only claim to fame and fortune is to be the first person along with his hiking partner Jarrod Gasper to backpack both the Pacific Crest Trail and Appalachian Trail (~4,650 miles) in one calendar year.