A Robust Mechanism to Dynamically Provide Grid Services with a Fleet of Plug-in Electric Vehicles

Yinyu Ye and Nicole Taheri

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Proposed Project Period: July 1, 2012 – June 30, 2013

Summary

Plug-in Electric Vehicles (PEVs) are a rapidly developing technology that can help to reduce greenhouse gas emissions and our dependence on foreign oil. PEVs will also be an integral part of the future smart grid, due to two main features: First, PEV charging stations will most likely be available at home and at work, offering flexible charging options. Second, these vehicles will have the capability of transmitting electricity back to the grid, known as a vehicle-to-grid (V2G) system. These features allow PEV charging and discharging to be distributed among vehicles in order to benefit the consumer, who may profit from charging when electricity prices are relatively low and discharging when the electricity prices are higher. Moreover, a fleet of vehicles can be used to provide grid services for electric utilities. Utility companies may utilize PEVs as distributed energy storage devices that store surplus electricity generation to be transferred back to the grid in times of deficit, which will assist the integration of variable generation via renewable energy resources into the grid. However, along with these benefits come challenges and risks. For example, how will PEVs impact the stability of power grid? What type of market mechanism would be most efficient to organize this distributed trading? Are there new business and service industries that could be created to manage PEVs? Our proposed project aims to address these questions and challenges. In particular, we propose to construct an automated Demand Response (DR) mechanism for a fleet of PEVs that defines the role of electric vehicles in a smart grid. An aggregator, a new service unit, will communicate energy needs between a fleet and a utility, and regulate consumer electricity use to yield a beneficial transfer of energy. The DR aggregator uses a simple price equilibrium to instantly and automatically determine feasible energy exchange schedules for tens of thousands of vehicles as they plug-in to the grid, based only on a relatively small amount of aggregated historical data. Moreover, fleet charging of vehicles would be managed to stay within bounds placed by utilities. The charging and discharging schedules are robust to unexpected events, and reduce the consumer cost of charging a PEV. These generated schedules can result in a balance of electricity supply and demand and ensure that a new demand peak is not created, which are key features to maintaining the stability of the electricity grid.

1 Problem Statement

A Plug-in Electric Vehicle (PEV) is any vehicle that uses electricity from the grid to displace liquid fuel. PEVs currently on the market are able to plug-in to the electricity grid and control which times during the connection period the vehicle battery will actually charge [11]. This feature will allow consumers to charge their vehicles when the price of electricity is relatively low. The future electric vehicle will incorporate a number of new technologies. Specifically, we consider the ability of vehicles to transmit electricity back to the grid, or provide vehicle-to-grid (V2G) services [12]. This capability could benefit both consumers and utilities, by helping to cultivate a balance between the electricity supply and the demand and reducing the cost of charging to consumers. A new mechanism is needed to regulate this trading in an electricity market between PEVs and the utilities, while maintaining the stability of the grid.

For example, suppose a vehicle is plugged in from 6pm until 7am, giving an 11-hour window in which the vehicle is connected to the grid. If the battery can obtain sufficient charge in one hour, the charging could occur during the hour between 6pm and 7am when the electricity price is the lowest. The remaining 10 hours can be spent transferring an equal amount of energy to and from the grid: storing electricity during periods of low power demand and transmitting energy back to the grid when the demand is high. This will also typically result in a monetary profit for the consumer.

We plan to construct an automated mechanism that defines the participation of plug-in electric vehicles on a smart grid, by implementing Demand Response (DR) services with a fleet of PEVs. This service will be managed by a new service between fleets of vehicles and utilities, called an *aggregator*. The aggregator will schedule a transfer of electricity that will distribute a sufficient amount of energy to each vehicle, ensure a reduced cost to the PEV owner, and meet a scheduling obligation made by the utility. Such regulation leads to a reduction in peak power loads, promotes the integration of renewable energy generation and can motivate consumers to buy vehicles that depend less on oil than their gasoline-powered counterparts. Our algorithm will use linear programming to determine equilibrium prices for each hour that account for the charging needs of the fleet, vehicle driving schedules, current electricity pricing and a market scheduling obligation. Energy exchange schedules based on this pricing will be determined instantly as vehicles plug-in, without depending on information regarding other vehicles in the fleet during the connection period. The resulting energy exchange will ensure each vehicle is sufficiently charged, while attempting to balance the electricity supply and demand.

1.1 Background

Current PEV charging stations allow management of charging, where the user is required to select and program the exact charging schedule [11]. These charging stations are not capable of automatically scheduling the vehicle to to charge during the period with the lowest expected electricity price, or lowest demand. There is a need among aggregators for an automated DR mechanism that manages the market between a fleet of PEVs (say, around 10,000 vehicles) and their utility, to minimize the cost to the consumers and meet an obligation to the utility.

Currently, aggregators between consumers and electric utilities are either third-party companies (such as EnerNoc or ZigBee) or are run by the utilities themselves (both PG&E and Duke Energy have DR programs, among others). These aggregators regulate demand to meet a scheduling obligation to the market, or system dispatcher, by rewarding decreases in electricity use during certain time periods. However, existing programs focus on the Commercial and Industrial Sector, with a small number of large customers who typically use hundreds of kilowatt hours (kWh) per day [19]. These programs are not automated, requiring human intervention to individually tailor the DR resource for each customer and monitor the electricity use of each customer alongside the market supply and prices.

By contrast, some estimates say there may be 100 million PEVs on the road in the United States by 2030 [7] and each PEV battery will generally require a few kWh each day. Moreover, a V2G system will require unique management oversight for a mutual electricity transfer. Due to the expected prevalence and size of PEV fleets, DR services for a fleet of PEVs providing unprecedented energy exchange cannot be individually monitored for each vehicle. Aggregators need an automated mechanism to facilitate the charging and discharging schedules of the fleet to meet the needs of the vehicles and satisfy a scheduling obligation to the market.

1.2 Related Work

A number of papers in the field of electric transportation have established the benefits of smart charging, including [3, 6, 13, 21]. However, there is currently no standard agreement on how to manage a mutual energy exchange between PEVs and the grid. A number of previous works consider V2G, yet depend on the knowledge of exact driver behaviors and energy needs of all vehicles in the fleet prior to determining the energy exchange of any individual vehicle, i.e., these mechanisms are not dynamic. There has also been work that dynamically regulates PEV energy use, but these algorithms do not consider a scheduling obligation that needs to be met and are not robust to unexpected events. Moreover, we feel that no algorithm suggested has been realistically implementable.

For example, Han et al. in [8] use dynamic programming to assign charging schedules that provide frequency regulation. Similarly, in the work by Wu et al. [22] an algorithm is constructed that makes dynamic decisions for lowest-cost charging schedules of PEVs. Neither of these works considers a scheduling obligation, and the demand of each vehicle is considered individually (i.e., not as part of a fleet); both suggested algorithms would result in an increased peak demand. In [9], Ma et al. establish a decentralized algorithm that determines an equilibrium price so that the total amount of charging done in the fleet fills the 'overnight demand valley.' This algorithm takes into account all vehicles in the fleet, but is not dynamic since it requires all vehicles to be connected to the grid at the same time and exactly report their future driving schedule; this work also assumes only a few types of driving behaviors exist.

2 Objectives

We plan to construct a DR service for PEVs that is simple and thorough in design. The service will be understandable and trustworthy for both consumers and utilities, and its implementation can result in substantial benefit for both parties.

A PEV fleet aggregator will determine energy exchange schedules for each vehicle that ensure the needs of both the PEV consumers and the utility are met. First, the aggregator communicates with the utility to agree upon a scheduling obligation, possibly in the form of upper and lower bounds on electricity usage over time. Next, as vehicles plug-in to the grid at various times, the aggregator will instantly determine at which times during a vehicle's connection it should charge and discharge. Our algorithm will construct energy exchange schedules that:

· are assigned instantly as vehicles plug-in to the grid,
· provide enough charge to each individual PEV to meet its daily transport load,
· meet the obligation to the market,
· maintain grid stability,
· consider the demand of the fleet as a whole, and
· reduce the cost (or increase the profit) to the consumer.

Our mechanism will be easily used by a fleet aggregator to perform demand response. The implementation will be very simple: a unique set of adjusted prices will be constructed that accounts for the current electricity and gasoline prices, electricity load and amount of power "available", the energy demand of each vehicle, and individual vehicle characteristics. Allocating vehicle charging to hours when the adjusted price is lowest and discharging to the hours with higher adjusted price values will result in an exchange of energy that maximizes consumer profit and balances supply and demand.

2.1 Proposed Research

We aim to establish the role of a new service between utilities and consumers, which manages the electricity trading market and maintains stability on the grid. Our pricing scheme will depend only on historical data, and will not need to predict or know a priori the driving patterns of each vehicle in the fleet. We will use real data on driving behaviors, electricity loads, electricity and gasoline pricing, and vehicle characteristics to show our mechanism will work in realistic scenarios.

In order to estimate the availability of vehicles to the grid (i.e., their connection times) and vehicle transport loads, we use clustering. Specifically, we plan to use the k-means clustering algorithm with Euclidean distances on the transport loads of simulated fleets. We define a *base* driving profile to be the "best-fit" to a group of drivers with similar driving patterns. Based on the portion of drivers corresponding to each base profile, the availability and needs of a fleet of vehicle can be approximated. Actual driving behaviors can be obtained from the National Household Transportation Survey (NHTS) [18], which contains the driving schedule of over 150,000 individuals, each for a 24-hour period.

Once we have formed k base driving profiles based on previous, similar days, the aggregator can form a linear program to find the optimal exchange of energy for each base driving profile. We can use the results of this linear program and its dual to establish an 'equilibrium price' for energy during each time period, or hour. If charging and discharging schedules are determined based on this price, there will be an optimal energy exchange that maximizes consumer profit and meets the scheduling obligation with the utility, while providing each vehicle with enough energy to drive.

To determine such energy exchange schedules, we assume the aggregator can learn from each vehicle its expected driving schedule for the next n hours and the vehicle characteristics. We will consider Plug-in Hybrid Electric Vehicles (PHEVs) that receive power from both gasoline and electricity, in addition to Battery Electric Vehicles (BEVs) that only receive power from an electric motor. We also assume the aggregator knows the electricity and gasoline prices at each hour and has committed to a scheduling obligation with the utility, for example, the utility may place upper and lower bounds on total electricity usage of the fleet during given time periods.

In our current work [17], we construct *constraint-adjusted prices*, which use the dual variables from a linear program to determine an allocation of charging to vehicles. Each cluster has a distinct set of constraint-adjusted prices such that allocating charge according to these prices will ensure the additional electricity load caused by charging the fleet will stay below an upper bound determined by the utility. Real electricity load and pricing data are used, from sources listed in [16], and the scheduling obligation to the utility ensures that the daily peak demand will not increase.

Our future work will use our previous formulation and implementation as a platform, from which we can create a simpler mechanism that will determine both charging and discharging schedules to meet a wider range of scheduling obligations. We will construct an equilibrium price that can be used to determine the charging and discharging schedules of each vehicle, and result in a schedule of energy transfer that is of the lowest cost to the consumer and attempts to balance the electricity supply with the demand.

We plan to construct a mechanism that is realistically implementable for the aggregator. Using real data, we will show that an aggregator using our equilibrium price algorithm will provide a DR service that is robust to unexpected events [5]. This price will be based on historical data, and may employ dynamic prediction market techniques to learn the distribution of the trading population, such as [1]. Vehicle charging and discharging allocated using our price equilibrium will lead to schedules that maximize the consumer's profit and meet the energy needs of each vehicles, while meeting the scheduling obligation.

2.2 Significance

Regulating the electricity usage of PEVs will reduce the cost of charging to the consumer, and reduce the increase in electricity peak demand. It is projected that by the year 2030, between 6% and 30% of vehicles in use will be PEVs [6], which suggests a possible increase in electricity demand due to PEV charging. In [6], the Electric Power Research Institute (EPRI) showed that in the worst case, the increase in total grid capacity will be 5-6%, where as shifting some charging to off-peak hours will decrease the impact to only 1-2%. In a collaborative work between Better Place and PJM Interconnection [14], Schneider et al. showed that such controlled charging will reduce consumer energy costs by 45% .

Moreover, as mentioned in Section 3.1 below, PEVs will encourage the integration of renewable energy generation into the grid, by providing a distributed energy storage resource. PEVs can also provide frequency regulation to help improve the stability of the grid. Using PEVs to provide grid service is an essential part of the future grid.

3 Expected Interest

There are a number of third-party aggregators and utilities currently providing DR services to large customers, mostly in the commercial and industry sector. These programs require individual monitoring and human intervention to motivate reductions in electricity usage. When these aggregators extend their services to households and PEVs, they will need an automated algorithm to facilitate a beneficial and stable transfer of energy.

The energy requirements of electric vehicles are extremely unique. First, at any given time, the majority of vehicles are stationary, or parked. For example, [4] shows that on any given day 54% of vehicles are not driven at all. The same work also shows that 90% of vehicles start and end their days at home, implying that there is a substantial window of time every night when the vehicle will possibly be plugged-in with the potential for both charging and discharging with no effect to the consumer. Furthermore, the energy needs of a vehicle can be estimated fairly well by the driver, for a limited amount of time into the future, say 24 hours.

We plan to design a mechanism specifically for PEVs that could be used by current DR aggregators. Moreover, our algorithm will result in substantial monetary profits and environmental offsets to motivate consumer participation.

3.1 Benefits

Plug-in electric vehicles will run off of electricity provided by the grid, which can be generated sustainably. Thus, when more consumers choose PEVs over gasoline-powered vehicles, it reduces greenhouse gas emissions and our dependence on oil. However, many consumers need more specific motivation to buy PEVs. An implementation of our algorithm by an aggregator will result in a daily monetary profit for the consumer, in addition to maintaining the stability of the electricity grid and environmental offsets.

Furthermore, PEVs that participate in a V2G demand response program can help to take full advantage of renewable energy. Renewable energy sources provide sustainable electricity generation, but result in variable and uncertain production levels. Energy storage is needed to store excess electricity during periods of surplus that can be used later in times of deficit. However, the large capital required for centralized energy storage has been a difficult obstacle to overcome. Thus, using PEVs as distributed storage has become a common solution in the energy storage field. A fleet of PEVs providing grid service will help make renewable energy resources a more practical integration into the current electricity grid, in addition to helping improve the stability of the future electricity grid by providing frequency regulation [15].

Many renewable power plants generate more electricity than is needed during off-peak hours, and a lack of sufficient energy storage means this surplus cannot always be stored for later use to meet the demand. For example, during the first half of 2008, an overproduction of wind power in West Texas led to negative electricity prices 20% of the time, and most of this surplus occurred in the middle of the night [20]. If vehicles had been connected to the grid with a DR mechanism, they may have actually profited from charging their batteries during these time periods and storing the surplus energy for later use.

3.2 Feasibility

Our mechanism can be implemented within a device attached to each individual vehicle in a fleet; these devices can communicate with each other and regulate vehicle charging, in order to maximally benefit the market and maintain grid stability. Such a device is a practical extension of services that are currently provided with PEV charging stations, which allow the user to control charging but require settings to be determined by the user [11]. An aggregator's role is between these devices and the dispatcher to establish and monitor the market supply and vehicle demand. Currently, an infrastructure that allows such regulation of charging is in the initial development stages [10]. With such an infrastructure in place, aggregators will need an algorithm to automate the process of using PEVs as a DR resource.

It should be mentioned that such managed charging is envisioned to be an 'opt in' service that a consumer has the option to participate in. Consumers can sign up with an aggregator that manages electricity trading with their utility. Some consumers may not be willing to offer their vehicles as energy storage devices to benefit the grid, however we hope to show that the monetary profit and environmental offsets that can be achieved by participating in such a service will provide substantial motivation for consumers.

3.3 More Research Directions

Aggregation of consumers to provide an automated DR resource to a smart grid is a service that can be extended to entire households. The future electricity grid will allow consumers to regulate their electricity use in reaction to market prices and supply. In a household, there are a number of appliances for which the exact usage time is not critical. For instance, a dishwasher could be set to run overnight, during the time when electricity price is lowest before 8am. Such guidance of electricity usage will require an automated mechanism between the consumers and the electricity market. This regulation will depend on an automated system similar to our mechanism to determine energy exchange schedules of PEVs. However, demand response methods for complete households is very different from providing grid services with PEVs. We plan to continue extensions on this work that design mechanisms for a smarter grid.

4 Research Team

The research team for this project is a multidisciplinary group of researchers from industry and a range of departments at Stanford. The lead Principal Investigator (PI) will be Yinyu Ye, Professor of Management Science and Engineering, and the team members will include Nicole Taheri (graduate student in the Institute for Computational and Mathematical Engineering), Bob Eberhart (graduate student in Management Science and Engineering), Emmanuel Tsukerman (undergraduate student in Mathematics), and Robert Entriken (Senior Project Manager, Electric Power Research Institute).

This project tackles an interdisciplinary problem that requires knowledge and research in a number of different fields, relying on each team member to play an essential role. Nicole, Emmanuel and Yinyu will apply Mathematical Programming, Bob will contribute his background in Economics and Robert will provide his expertise in Power Networks and a Smart Grid. Nicole, Yinyu and Robert have been working on an EPRI funded project entitled “Robust and Dynamic Market Decisions for Plug-in Electric Vehicles” since April 1, 2010.

References

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Budget Justification

The budget would mainly be used to support two graduate student research assistants and one undergraduate student summer research assistant.

RFP Due Date: December 19, 2011
Project Start Date: July 1, 2012
Project End Date: June 30, 2013

Project Personnel	**% Effort**	**9 months**	**12 months**
PI (Academic Council Member or MCL)	7%		$14,680
Graduate Students	50%		$50,301
Undergraduate Students (Contingent)	50%		$8,383.5

Non-Salary Expense

Material and Supplies	$1,000
Travel	$5,000
Publications	$1,000
Computer Supplies/Software	$2,000
Tuition	$37,635

Total Amount Requested: $120,000

Principal Investigators

Current support: *Yinyu Ye*

PI: Yinyu Ye
Project/Proposal Title: "Dynamic Market Model for Plug-in Electric Vehicles"
Source of Support: Electric Power Research Institute (EPRI)
Total Award Amount: $120,000,
Total Award Period Covered: 4/1/10 – 9/31/12,
Person-Months Per Year Committed to the Project: Cal: 0 Acad: 0.1 Summ: 0

PI: Michael Saunders and Co-PI: Yinyu Ye
Project/Proposal Title: "Numerical Optimization Algorithms and Software for Systems Biology"
Source of Support: DOE, DE-SC0002009
Total Award Amount: $1,458,940
Total Award Period Covered: 9/15/09 – 9/14/12
Person-Months Per Year Committed to the Project: Cal: 0 Acad: 0 Summ: 1.

PIs: Tom Luo, Jongshi Pang, and Yinyu Ye
Project/Proposal Title: "Optimization Algorithms and Equilibrium Analysis for Dynamic Resource Allocation"
Source of Support: Air Force Grant, FA9550-09-1-0306
Total Award Amount: $750,000
Total Award Period Covered: 4/1/09 – 3/31/12
Person-Months Per Year Committed to the Project: Cal: 0 Acad: 0.3 Summ: 0.7

PI: Yinyu Ye, Co-PI: Boeing Company
Project/Proposal Title: "GOALI: Region Partitioning"
Source of Support: NSF, NSF GOALI 0800151
Total Award Amount: $318,000
Total Award Period Covered: 7/1/08 – 6/30/11
Person-Months Per Year Committed to the Project: Cal: 0 Acad: 0 Summ: 0.3

PI: Yinyu Ye
Project/Proposal Title: "Stochastic/Robust Dynamic Resource Allocation"
Source of Support: Boeing
Total Award Amount: $1,676,250
Total Award Period Covered: 7/1/04 – 12/31/10
Person-Months Per Year Committed to the Project: Cal: 0 Acad: 1.0 Summ: 0

Curriculum Vitae: *Yinyu Ye*

Professional Preparation

· Huazhong University of Science and Technology (HUST), China. EE B.S., 1982

· Stanford University EES and OR Ph.D., 1988

Appointments

· 05/02 – present: Professor, Department of Management Science and Engineering and by courtesy, Electrical Engineering, Stanford University.

· 09/93 – 04/02: Henry Tippie Professor, Department of Management Sciences and Applied Mathematical and Computational Sciences, The University of Iowa.

· 09/90 – 8/93: Associate Professor, Department of Management Sciences, The University of Iowa.

· 09/88 – 08/90: Assistant Professor, Department of Management Sciences, The University of Iowa.

Synergistic Activities

· Recipient of the 2009 John von Neumann Theory Prize

· Recipient of the 2009 IBM Faculty Award.

· Chairman of the technical advisory board of MOSEK, an Optimization Software company.

· Optimization Area Editor of Mathematics of Operations Research (2009-), Optimization Area Editor of Operations Research (2005-2009).

· E. Delage, The First Prize of INFORMS Nicholson Student Paper Competition, 2008, for his Ph.D. Thesis supervised by Y. Ye: Distributionally Robust Optimization under Moment Uncertainty with Application to Data-Driven Problems

· Recipient of the 2007 Stanford Asian American Faculty of Year Award.

· The inaugural recipient of the Farkas Prize of the INFORMS Optimization Society (awarded bi-annually), 2006.

· Elected as an INFORMS Fellow, 2006.

· Plenary speaker at the 19th International Symposium on Mathematical Programming, Rio de Janeiro, 2006; Semi-plenary speaker at the 17th International Symposium on Mathematical Programming, Atlanta, 2000.

Collaborators & Other Affiliations

Thesis Advisor: George Dantzig (Stanford), David Luenberger (Stanford), Edison Tse (Stanford). Member of The Institute for Operations Research and the Management Sciences (INFORMS) and Mathematical Optimization Society (MOS). Elected Vice Chair of the SIAM Activity Group on Optimization (SIAG/OPT), 2008 – present.