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Communication and Control of Electric Vehicles Supporting Renewables

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Communication and Control of Electric Drive Vehicles Supporting Renewables

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Abstract— **The coming intersection between a growing electrified vehicle fleet and desired growth in renewable electricity generation presents an opportunity for synergistic value. Some types of renewable electricity generation are variable and intermittent and are rarely coincident with utility load patterns. Vehicles are typically parked 90% of the time, and the batteries are a significant capital investment. In this paper we discuss the intersection of these two growth areas, the technology needed for integration, and several potential scenarios highlighting the limitations and opportunities for renewable energy resources to fuel electrified vehicles of the future.**

Keywords- Electric vehicle, EV, PEV, PHEV, plug-in hybrid, PHEV; vehicle to grid, V2G; renewable energy integration; renewable energy variability.

I. Introduction

Renewable energy (RE) generation capacity is growing rapidly – the United States increased wind power generating capacity by 5.24 GW in 2007 alone, a 45% increase over wind power generating capacity in 2006 [1]. Currently, 24 states have renewable portfolio standards (RPS), which are legally binding RE generation targets that utilities must achieve by a specific date [2]. While these renewable energy targets are an important step in reducing fossil fuel consumption and greenhouse gas emissions, some renewable resources, such as wind and solar, have an integration challenge: they are non-dispatchable, unlike hydro or concentrating solar power. This means that wind and solar units cannot be commanded to increase or decrease output power, despite constantly changing consumer demand. This nondispatchable subset of RE generation is the focus of this paper.

Several solutions to RE dispatchability challenges are currently being employed, including increasing operational reserves (usually fossil fuel units), storing renewable energy using a variety of emerging methods, and demand-side management programs [3, 4].

Demand-side management programs include energy efficiency and conservation, peak-shaving by shifting bulk loads, and demand response [5]. Shifting bulk loads and demand response programs require communication between consumers and producers of energy and will be more widely enabled with the expansion of grid communication networks across the country [6]. Plug-in electric vehicles (PEVs) could support RE expansions through any of the three options listed: reserves, storage, and demand-side management.

Charging schemes based on grid communication of real-time load, price, and RE generation are developed and discussed. The first half of the analysis describes the modeling tool that was developed in MATLAB™. The second half of the analysis describes physical-layer grid-networking technologies and evaluates each technology based on its suitability for grid communication purposes. Finally, simulation results are presented for several cases in the Los Angeles area.

II. Vehicle Fleet-Grid Interaction Model

The interaction between plug-in vehicles and the power grid is modeled using several real-world data sets to simulate driver behavior, vehicle systems, and the power grid. The simulator takes these inputs and models the data and power transactions that occur between the vehicles and the power utility, calculating the fuel consumed, battery wear, data throughput, load and ramping characteristics of the PEV fleet and renewable generation, and overall operating cost for the various system architectures. Each subsystem included in the model is described in detail below.

A. GPS Travel Survey Data and Vehicle Model

GPS travel survey data were collected by the Southern California Association of Governments as part of its transportation planning process. A total of 621 unique vehicles were instrumented with GPS data loggers between October 2001 and February 2002, and they recorded 1144 24-hour driving profiles. Each data file includes a 1 Hz record of time, speed, and location. Plug-in hybrid electric vehicle (PHEV) operation was simulated over each driving profile.

The vehicle model is a parallel hybrid that operates in a charge-depleting (CD) mode, then reverts to a charge-sustaining (CS) mode when the battery state-of-charge (SOC) falls below 35%. In CD mode, the model assumes a battery power consumption rate of 0.18 kWh/km (0.29 kWh/mi) and a fuel consumption rate of 1.5 L/100 km (157 mpg). In CS mode, the model assumes a fuel consumption rate of 5.2 L/100 km (45 mpg). The battery pack holds 9 kWh of energy, of which 5.85 kWh are usable, giving the vehicle an electric range of 32 kilometers (20 miles). The battery wear model is based on the real-time (RT) lithium-ion battery modeled in [7], and assumes a battery cost of $900, $600, and $300/kWh for the three scenarios, as shown in Table 1. The $300/kWh scenario is below the current market price for lithium ion batteries and was chosen to represent the scenario in which the U.S. Department of Energy (DOE) battery cost target is met. The three scenarios represent near-, mid-, and long-term RE and PHEV adoption goals. The vehicle's battery charger and power electronics operate at 90% efficiency. Power and fuel consumption are calculated by integrating the second-by-second distance traveled. The battery wear is based on the daily maximum discharge, and calculated according to the corresponding lifetime cycles using the battery life model. The instantaneous vehicle-to-grid (V2G) offering price calculation is described in (1):

$$MP_{V2G} = \frac{\mathrm{C_{ESS}}}{\mathrm{n_{SOC}} \cdot \mathrm{E_{avail}}} + \mathrm{MP_{min}} \qquad (1)$$

where MP_{V2G} is the real-time offering price for the energy in the vehicle's battery pack, $\mathrm{C_{ESS}}$ is the cost of the battery pack, $\mathrm{n_{SOC}}$ is the number of lifetime discharge cycles at the current state of charge, $\mathrm{E_{avail}}$ is the RT energy available in the battery pack, and $\mathrm{MP_{min}}$ is the base price of electricity, representing the cost originally paid to get the energy into the battery.

All vehicles plug into a 240 V/30 A outlet, operating at a maximum of 20 A, for a maximum charging rate of 4.8 kW. At this rate, vehicles completely charge within two hours.

B. Utility Load & Renewable Energy Generation Data

The utility load and price data used for this analysis come from the 2005 FERC filings for Los Angeles Department of Water and Power [8]. The hourly data are interpolated to fit the 10-second time step of the simulation. In the V2G-enabled scenarios, vehicles are paid for spinning reserve services based on the available kilowatt-hours in the battery pack. The wind energy data (Fig. 1) are based on NREL's Western Wind Resources Dataset [9]. The wind turbines surrounding the Los Angeles area were chosen to simulate the wind power tied to the local grid; 10-minute wind data were aggregated from the wind farms located between 33.67ºN and 36.06ºN, and 116.16ºW and 119.17ºW, as shown in Fig. 1. To simulate a range of wind energy penetration levels, the data were integrated over the full-year data set to match the full-year load data, then scaled to simulate the desired penetration percentage. For the solar power profile, data from [10] were used and averaged over 10-minute intervals to represent the power output shape of an agglomeration of PV plants. Load and ramp rates were calculated to evaluate the impacts of the plug-in fleet and RE generation.

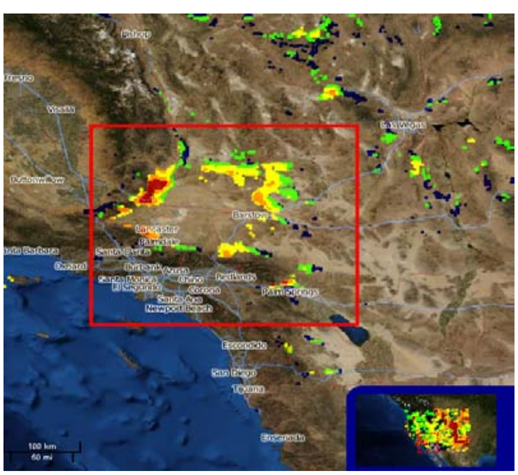

Figure 1. Map of the area from which wind farm data were aggregated to simulate wind power generation (from NREL's Western Wind Data Set)

III. Control Algorithms

A variety of fleet control methods have been suggested in the literature [11]. Of the proposed methods, three promising fleet charge-control methods are demonstrated here: price-signal-based charging, load-signal-based charging, and RE-based charging. The three scenarios will be compared with a baseline case of 4.8 kW opportunity charging, meaning that the vehicles are assumed to be plugged in and charged as soon as they are parked. The PHEV adoption cases were chosen to emulate the adoption of traditional hybrid vehicles. Scenario 1 represents a near-term PHEV adoption scenario with a conservatively chosen battery price. By contrast, scenario 3 represents a longer-term scenario with more ambitious PHEV adoption and RE penetration rates, as well as a low battery cost. All scenarios are summarized in Table 1.

TABLE I. Simulation Scenarios

Simulation Scenarios – Opportunity, Price, Load, and RE-based Charge-Control			
Scenario #	PHEV Adoption %	Annual % Energy from Wind and Solar	Battery Price
1	1%	15%	$900/kWh
2	5%	20%	$600/kWh
3	20%	40%	$300/kWh

A. Opportunity Charging

The opportunity charging scenario assumes a pervasive EV charging infrastructure. All vehicles charge at the 4.8 kW rate and 90% efficiency as soon as they are parked and continue charging until the battery pack is fully charged. No communication or V2G services are offered.

B. Price-Signal Charging

Price-signal-based charging presumes a one- or two-way communication network and is based on the RT price of electricity. In this scheme, the PHEVs passively listen to the utility's broadcast of the charging rate. The vehicle charging rate is calculated using (2),

$$r_{RT} = R_{MAX} \cdot \left(1 - \frac{MP - MP_{min}}{MP_{max} - MP_{min}}\right) \qquad (2)$$

where r_{RT} is the real-time charging rate in kW, R_{MAX} is the maximum physically allowable charge rate in kW, MP is the real-time marginal price of electricity from the utility in

\$/MW, and MP_{min} and MP_{max} are the daily minimum and maximum RT marginal prices for the day in \$/MW.

The daily minimum and maximum prices correspond to the bounds of the charging rate (0-4.8 kW). Therefore, if the RT price of electricity is equal to the maximum 24-hour price of electricity, the charge rate goes to zero. If the RT price of electricity is equal to the minimum 24-hour price of electricity, the charge rate reaches the maximum value of 4.8 kW. When the RT price of electricity is below a PHEV's offering price, power is supplied to the grid from the vehicle's battery.

C. Load-Signal Charging

The load-signal-based charging scheme is identical to the price-signal-based algorithm, except that the maximum and minimum charge rates are defined by the RT load rather than the price. The vehicle charging rate is calculated using (3),

$$r_{RT} = R_{MAX} \cdot \frac{L_{RT} - L_{min}}{L_{max} - L_{min}} \tag{3}$$

where L_{RT} is the RT utility load in megawatts, and L_{max} and L_{min} are maximum and minimum daily loads in megawatts.

As in the price-signal algorithm, a communication network is presumed, and V2G energy is supplied when the RT price of electricity is lower than the PHEV offering price. The power supplied to the grid is proportional to the load and calculated using (3).

D. Renewable Energy-Signal Charging

Renewable-energy-signal charging is based on the premise that the plug-in fleet can be charged "exclusively" using renewable energy, with plug-in vehicles acting as an energy sink. During windy or sunny conditions, the PHEV fleet absorbs bulk power generated by wind and solar farms. During low-renewable-power conditions, the vehicles charge at a slower rate. No wind or solar generation would normally result in no vehicle charging; however, if RE generation is zero, a base charging rate is set such that the vehicles will be able to fully charge within six hours. To accomplish this, a two-way communication network is needed. The utility receives a 1024-bit charging request from each vehicle at regular 10-second intervals. In a real-world implementation of this system, the data packets would include encoded vehicle identification information, charging requests, grid state and location information, and the battery pack SOC. The utility calculates a charging rate and broadcasts the information over the network. The charge rate is calculated in (4):

$$r_{RT} = \frac{P_{RE}}{\mathrm{n_{rq}}} \tag{4}$$

where P_{RE} is the power output of wind and solar in MW, and $\mathrm{n_{rq}}$ is the number of plugged-in vehicles requesting to charge.

Note that if the power output from RE sources is sufficiently high, the calculated charge rate may be higher than the rate physically allowed by the charging circuit, and the charge rate is clipped at the maximum 4.8 kW value. In an actual implementation of this scheme, communication dropouts are likely to occur. In this case, the vehicles would limit excessive transients from switching on and off by maintaining a constant charge rate until communication with the utility is reestablished. The V2G services are not offered in this scenario, since the purpose of the algorithm is to test whether a plug-in fleet can maintain the original load profile using down-regulation only.

IV. Grid Communication Networks

Plug-in vehicle charging coincident with the existing peak load requires capacity expansion. Communication with PHEVs and infrastructure could shift charging to off-peak times. Many utilities across the United States have already installed grid communication networks to enable load shifting [6]. However, a variety of methods for accomplishing grid communication exist, and a survey of grid-networking protocols is needed. This section attempts to summarize the technologies being deployed for grid communication purposes. Each technology is evaluated based on how well it provides low-power, low-throughput, high-security communication applicable to plug-in vehicles. Two-way data transfer between the customer and electric utility is assumed to be accomplished via internet protocol (IP) on the utility side. We consider three wireless technologies as well as broadband over power line (BPL). Interference issues, power consumption, and security merits of each protocol are discussed.

A. Overview

1) Broadband Over Powerline and HomePlug™

Broadband communication over power line, or more generally, power line communication, is a technology that utilizes existing power line conductors as data transmission lines. High-frequency data signals are superimposed on top of the distribution voltage. BPL can also be transmitted across medium-voltage lines, providing last-mile service that can then be tied to the nearest wide-area network. BPL has been deployed in a number of U.S. cities since 2005; however, radio interference can be an issue [13]. New installations transmit data only over residential-side power lines leading up to neighborhoods, reducing the antennae effect from medium-voltage power lines, with successful results [14]. Utility data would then have to continue its path to wide-area networks through traditional internet data carriers, such as cable or fiber optic.

2) IEEE 802.15.4 (Zigbee™)

Zigbee is a specialized protocol for small, self-programming mesh network devices based on the IEEE 802.15.4 wireless standard. Zigbee networks are ad hoc self-associating mesh or star networks [15]. Zigbee operates in

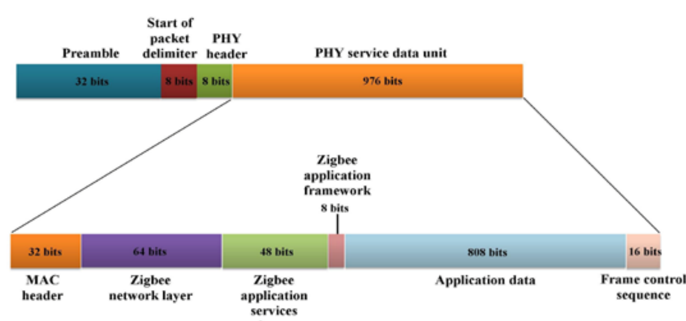

Figure 2. Anatomy of the simulated 1024-bit Zigbee data packets, based on [12]

both the 2.4 GHz and 900 GHz bands, giving Zigbee the flexibility to choose a different frequency band in noisy radio environments. Zigbee is specifically designed for sensing and automation applications, so a number of power-reducing functions are written into the 802.15.4 standard. The throughput of Zigbee networks can reach 250 kbit/s [16].

3) ZWave™

The sole designed purpose of the ZWave protocol is home automation – HVAC, lighting, security, garage access, etc. [17]. ZWave devices automatically set up an ad hoc mesh network upon start-up [18]. Of the four protocols discussed, ZWave operates at the lowest data rate, 9.6 kbit/s, and is the only protocol operating exclusively in the 900 MHz frequency band.

4) Cellular Network

The cellular network is a widely available long-range wireless data network, making it a good option for highly mobile devices such as PEVs. Both the Global System for Mobile Communications (GSM) and Code Division Multiple Access (CDMA) network handle individual user data rates above 100 kbits/s [19].

B. Power Consumption

In general, power consumption is an important consideration for grid networking devices, since the power supplying the device may be a battery. However, networking devices in PEVs would likely be powered from the wall outlet; therefore, power consumption considerations will be discussed only briefly.

BPL/HomePlug products do not require batteries, because the power supplies to these devices are provided through the electrical network connection itself.

Zigbee devices are designed for low power consumption (<1 mW) and have found a niche in the digital electric metering device market, making Zigbee a likely option for plug-in vehicle communications. Electric meters spaced less than 100 m apart (line of sight) are within the radio range of Zigbee devices, making it a suitable protocol for urban and suburban environments, though not particularly for rural areas. While the IEEE 802.15.4 standard does not explicitly define a maximum power draw for Zigbee devices, much of the language in the standard inherently reduces power consumption, such as small interframe spacing times and low duty cycle transmit/sleep periods [20].

ZWave is another purpose-built standard for connecting battery-powered devices wirelessly and was first released in 2004. ZWave power-saving features are similar to Zigbee's, and include a duty-cycled power save/nontransmitting mode, in which the chip is powered down to just the internal clock.

Cellular devices consume more power than Zigbee and ZWave devices because of the larger range required of the transmitter; however, like any of the networking devices discussed, the power supply would likely come from the vehicle's connection to the wall outlet.

C. Interference

Because many different wireless protocols utilize the same industrial, medical, and scientific (ISM) bands, frequency congestion and interference can become an issue in network-populous areas. The 2.4 GHz band alone supports IEEE802.11b/g/n (Wifi™), IEEE802.15.4 (Zigbee), Bluetooth™, and cordless phone service. Interference between Wifi, Zigbee, and Bluetooth has been well documented in the literature [21, 22, 23]. Common coexistence mechanisms between the three standards on the 2.4 GHz band have been shown by Zeghdoud to greatly decrease packet collisions between Zigbee and WiFi networks operating together [21]. No explicit coexistence mechanisms or standards for WiFi-Zigbee are currently defined, so interference must be minimized by careful channel selection and thoughtful network management when in the presence of multiple standards operating on the 2.4 GHz band [21]. Cellular communication uses dedicated frequency bands, and hence there are fewer documented issues related to network traffic collisions.

D. Security

Perhaps most important of all is the need for grid networks to be secure from hackers seeking to gain access to the power grid. Parties with any level of data access to the power grid could potentially disrupt the normal flow of power. Unlike wired networks, the data transmission media in wireless networks (the air) is inherently public, which presents a unique security threat at the physical (PHY) layer.

Advanced Encryption Standard (AES)

HomePlug, Zigbee, and ZWave all use 128-bit AES encryption to secure data transmitted across the physical network. AES encryption is a 128-bit fixed-length block cipher, standardized in 2002 by the National Institute of Standards and Technology [24]. Successful attacks have not been documented, and the U.S. government has approved 192- and 256-bit keys for use in encrypting top-secret information [24].

Since HomePlug utilizes home electrical wires instead of shielded coaxial cable, BPL transmissions may be unintentionally transmitted into the air at radio frequencies [25]. Thus, HomePlug uses the same PHY layer encryption as Zigbee and ZWave, to prevent RF transmission from being intercepted by unwanted parties.

Cellular security has improved with the introduction of data-transfer via cellular telephone; however, the security may not be suitable enough for grid communication purposes. The current security protocol is an A5/3 stream cipher called KASUMI, and it is currently used in 3G networks. Alternative proposals for more secure cellular data encoding schemes have been proposed, such as the one developed by Soyjaudah, which is similar to AES [26].

V. Simulation Results

The simulation program was run through 12 different sub-scenarios using data from April 11, 2005. April 11 was chosen because it represents a typical utility load profile found in the 2005 Los Angeles (LA) data set, and the magnitude of the peak load is between the largest and smallest peak throughout the 2005 LA data set.

The daily operating cost of the PHEV fleet was compared with two other simulated fleets – a 7.84 L/100 km (30 mpg) vehicle fleet, which represents a typical light duty sedan, and a 4.7 L/100 km (50 mpg) vehicle fleet, to represent a traditional hybrid electric vehicle (HEV) fleet. The additional PHEV load was large enough to limit the charge rate only during peak hours. In the RE-based charging scenario, the RE generation was significantly greater than PHEV load, so the charge rate was never limited. Thus, the charging profiles for all scenarios are very similar.

Fig. 3 shows that the operating cost per vehicle remains relatively constant, regardless of PHEV fleet size. The PHEV fleet used 29% as much fuel as the conventional fleet and 49% as much fuel as the HEV fleet. The PHEV fleet's operating costs were between 50% and 62% less than those of the conventional vehicle fleet and between 16% and 27% less than those of the HEV fleet.

Fig. 4 shows the wear cost associated with large SOC charge/discharge cycling characteristic of PHEVs. The price- and load-based charging schemes incur a slightly higher

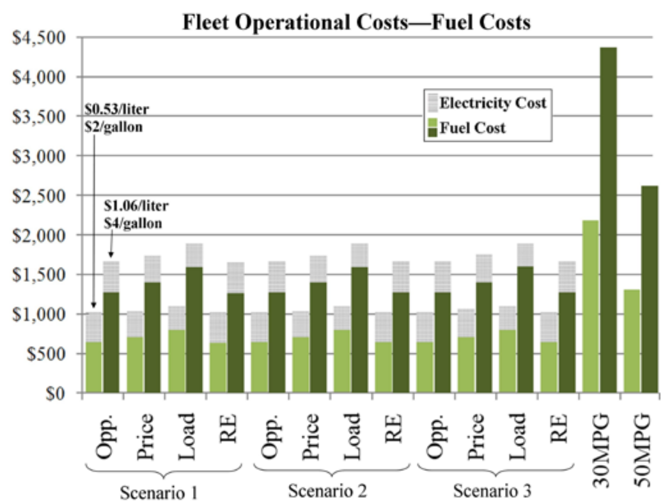

Figure 3. Daily fleet operating cost for all 12 scenarios at $0.53/liter ($2/gallon) and $1.06/liter ($4/gallon) fuel cost for April 11, 2005

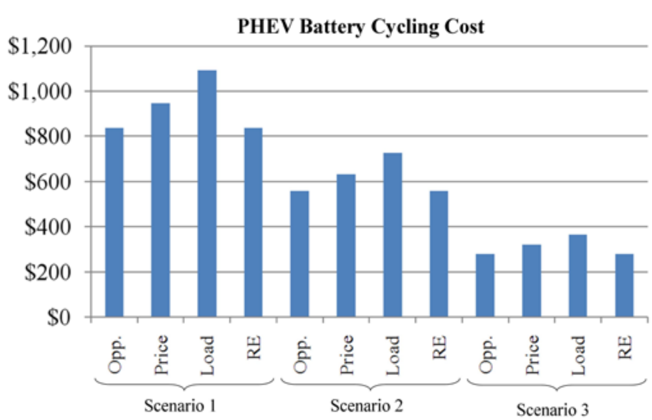

Figure 4. Battery wear cost for 12 scenarios

battery wear penalty than the other schemes. This is because the battery is not topped off as quickly as the other algorithms, allowing the battery to reach a lower state of charge. Because nearly all of the trips in the LA GPS drive cycle data were less than 32 km (20 miles), and charging takes place throughout the day between trips, the vehicles operated in CD mode about 80% of the time. The larger battery packs of the PHEVs allowed the vehicle to operate as an electric vehicle a majority of the time.

TABLE II. PEAK LOAD INCREASE – OPPORTUNITY CHARGING

Peak Load Increase, as a % of Peak Load			
PHEV Adoption	Increase in Peak Load Magnitude	Adjusted for Summer Peak	Adjusted for National Average
1%	0.60%	0.37%	0.23%
5%	3.03%	1.90%	1.18%
20%	12.47%	7.83%	4.87%

From a utility perspective, the opportunity-charged PHEV fleet added an additional load during peak hours roughly equal to the PHEV adoption percentage. Therefore, adoption of plug-in vehicles will necessitate either additional generating capacity or grid communication to shift the load to off-peak hours. The peak load increases caused by the opportunity-charged (no communication) fleet are summarized in Table 2. Because the simulation was run on a spring day, the resulting summer peak load increase was adjusted using data from the highest peak of the year on July 22. Finally, because per capita energy use in Los Angeles is about 38% lower than the national average [27], the data were additionally scaled to represent the change in summer peak load for a typical American city.

Based on simulation, a load- or RE-based charging scheme appears to maintain the peak load at its original value at a 20% PHEV adoption level. A load-based charge scenario reduces the need for capacity expansion without substantially increasing vehicle fuel consumption. The inclusion of RE supports vehicle charging while simultaneously reducing the peak load.

In the load- and price-based scenarios, V2G services are offered when the RT price of electricity is higher than the PHEV offering price. The RT utility price is plotted against the average fleet price for all three scenarios (Fig. 5). Utility price data from December 9 was added for reference because it had the highest peak electricity price of the year, at $137/MWh. Notice that when the battery cost reaches $600/kWh in scenario 2, V2G energy prices appear to match the utility prices, including battery wear.

Assuming that a one-way communication infrastructure is available, the price- and load-based charging algorithms are possible. The utility broadcasts the proportional charge rate based on the real-time price of electricity or load. The PHEV fleet load is plotted on top of the existing utility load for comparison in fig. 6, assuming a 5% PHEV adoption rate.

In the load-based case, the PHEV load is zero during the original peak, while the maximum power demand increases for both the opportunity charging and the price-based charging cases. Only the load-based charging algorithm maintains the daily maximum load at its original magnitude. Thus, the preliminary results suggest that a load-based charging scheme is an effective way to offset the need for additional generating capacity.

Finally, the ability of the PHEV fleet to serve as an energy sink for renewable power generation was tested. Fig. 7 illustrates the variability of RE generation at a 15% wind-solar integration level.

Fig. 8 demonstrates the interaction of PHEVs with RE generation under three scenarios. As shown in Fig. 9, the network traffic of all 1144 vehicles never exceeded 17 kbit/s, meaning that each vehicle is transmitting data at no more than 150 bit/s on average. This data rate is far below the maximum throughput capabilities of the networking options available.

The final simulations were based on the RE-charging scheme. Based on the PHEV adoption rate and RE deployment rate assumed here, the RE resources were more than enough to supply the PHEV fleet demands. PHEV

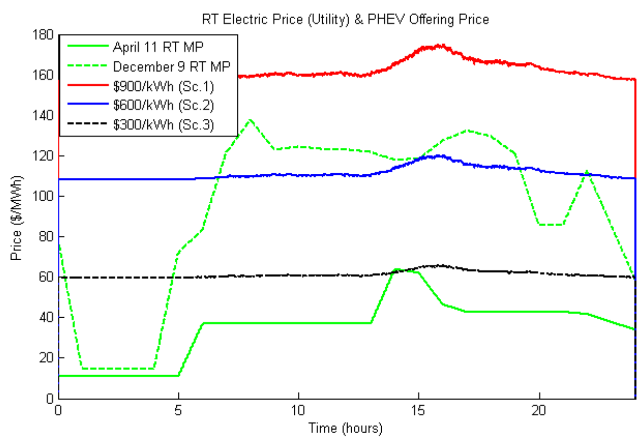

Figure 5. Real-time utility prices and PHEV fleet V2G offering prices, using the price-based algorithm

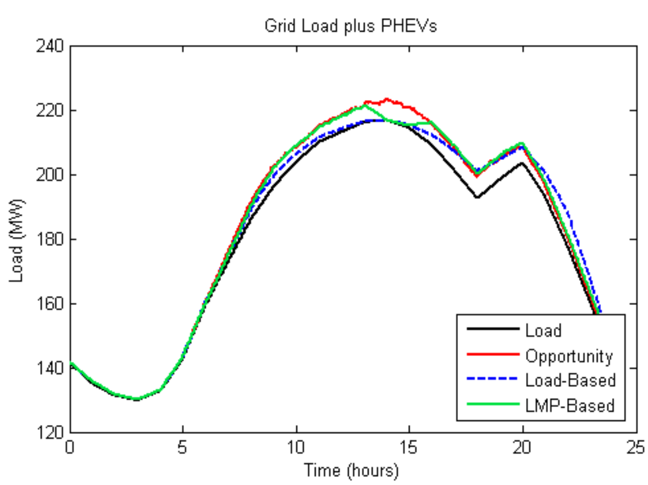

Figure 6. Utility load curve for April 11, 2005, assuming a 5% PHEV adoption rate. Opportunity, load-, and LMP-based charging load profiles are plotted on top of the existing load.

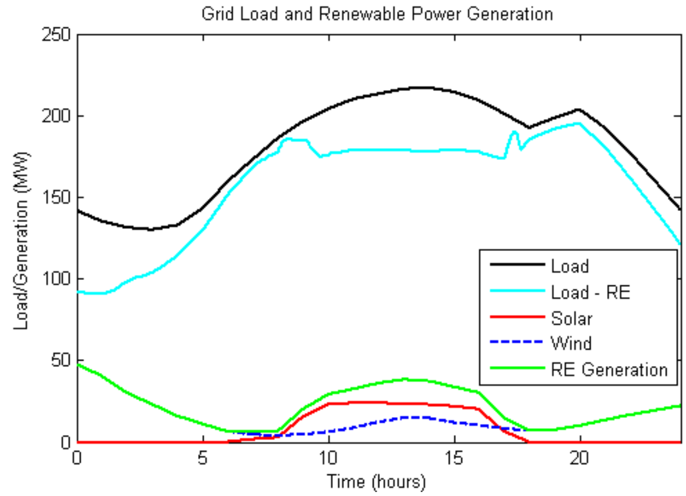

Figure 7. Utility load curve for April 11, 2005, assuming a 5% PHEV adoption rate. Opportunity, load-, and LMP-based charging load profiles are plotted on top of the existing load.

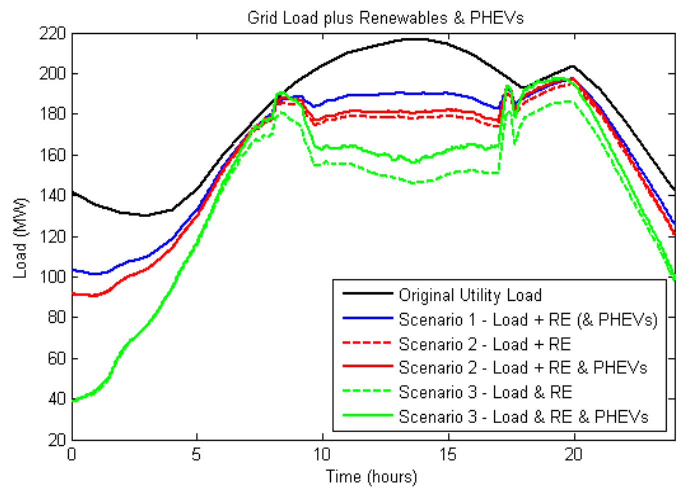

Figure 8. Scenario 3: Utility load curve, including renewable power generation and PHEV loads.

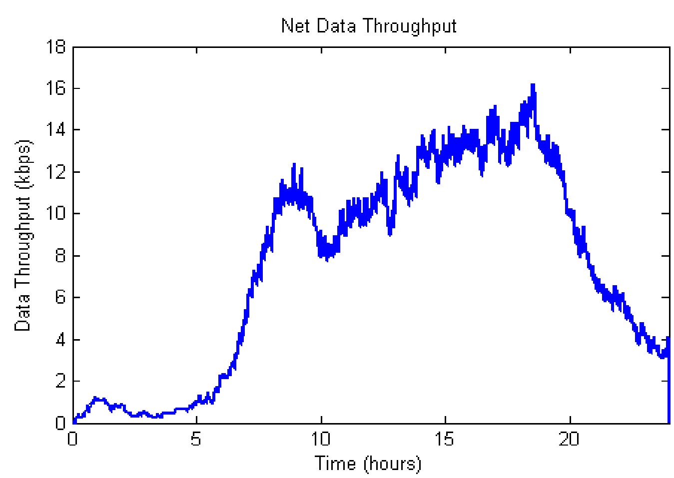

Figure 9. Throughput for renewables-based charging scenarios

charging in the RE scenario reduced the utility 10-minute ramp rates by 5%, in comparison to the case without PHEVs. Charge control schemes that help reduce RE ramp rates could provide value to the utility.

VI. Conclusion & Future Work

A MATLAB model for simulating the interaction between a plug-in hybrid fleet and the power grid was developed using GPS drive cycle data and utility load data as data inputs. Based on the simulation results, several observations were made:

- Based on the assumptions stated, PHEVs appear to be an economically competitive substitute for gasoline-only vehicles, including the cost of battery wear
- Grid communication networks have been shown to offset the need for additional generating capacity required to charge the simulated plug-in vehicle fleet
- Real-time price payments are sufficient to offset battery wear impacts when battery costs fall below $600/kWh, to support V2G
- Renewable energy generation is more than sufficient to charge the PHEV fleet, based on the growth rates assumed in the analysis
- BPL, Zigbee, ZWave, and cellular networks have sufficient throughput to relay IP data between PHEVs and the power utility to realize grid communication

Based on the results from the initial simulations, several aspects of PEV integration warrant further investigation:

- Higher time-resolution load and price data should be used to simulate regulation services and quantify the value to consumers and utilities
- The battery model should be expanded to include temperature effects on wear and efficiency, by linking to a meteorological database. Microcycle degradation should also be included
- A RE ramp rate-limiting algorithm should be explored
- Seasonal differences in load and generation should be simulated further
- A vehicle test fleet should be used to validate predictions regarding communication architecture and fleet charging control

The conclusions of this paper apply to an aggregate service area; distribution- and feeder-level effects have been excluded. Localized effects may limit the charge rate of vehicles concentrated on the same feeder; for an analysis of PEV impacts on distribution-level systems, refer to [28, 29, 30].

PHEVs were also shown to provide value to customers and the environment by reducing daily driving costs by 50% to 62% and lowering petroleum consumption by 71%, when compared with a standard 30 mpg vehicle fleet. Although the anticipated PHEV adoption rate implies that the energy sink would be too small to absorb bulk power from renewable energy generation, incentives that encourage more aggressive plug-in adoption rates might improve the grid-buffering capabilities of the PHEV fleet. By implementing a relatively low-throughput communication system, utilities may be able to reduce the extra capacity needed to serve PEVs. Grid communication networks enable load management and consumer participation toward RE expansion.

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The coming intersection between a growing electrified vehicle fleet and desired growth in renewable electricity generation presents an opportunity for synergistic value. Some types of renewable electricity generation are variable and intermittent, and rarely coincident with a utility's load pattern. Vehicles are typically parked 90% of the time, and the batteries are a significant capital investment. This paper discusses the intersection of these two growth areas, the technology needed for integration, and several potential scenarios highlighting the limitations and opportunities for renewable energy resources to fuel the electric vehicles of the future.

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