Impact Assessment of Plug-In Hybrid Vehicles on Pacific Northwest Distribution Systems

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***Abstract*--The U.S. electric power infrastructure is a significantly underutilized strategic asset which, with the proper shift in operational paradigms could provide a significant portion of the energy requirements for the existing U.S. light duty vehicle (LDV) fleet. This shift would result in reduced emissions, improved economics for utilities, and a reduced dependence on oil. A previous study has shown that the existing generation and transmission assets of the U.S. electric power infrastructure could feasibly supply the electricity for approximately 70% of the U.S. LDV fleet. In the limitations of the distribution system were not explicitly addressed and are more difficult to quantify because of the large diversity of distribution systems topology, design guidelines and load growth. This paper focuses on the impacts of a high penetration of Plug-In Electric Hybrid Vehicles (PHEVs) on the distribution systems. Presented are results specific for the Pacific Northwest.**

***Index Terms*--Power distribution, Power industry, Road vehicle electric propulsion.**

I. INTRODUCTION

The existing U.S. electricity infrastructure has been designed to meet the expected peak system load, similar to the interstate highway system. Similar to the interstate highway system the electricity infrastructure is only at peak capacity for a fraction of the time. The vast majority of the time the infrastructure is capable of delivering significantly more power. This is especially true of residential end users where the peak consumption of power generally occurs in the early morning and evening, with a substantial reduction in consumption at night.

Previous work has shown that the existing generation and transmission infrastructure has the technical potential to supply the power necessary for approximately 70% of the U.S. light duty vehicle (LDV) fleet (i.e., cars, pick-up trucks, vans, SUVs) [1]. This percentage is a national average and the actual values vary significantly depending on the region. For the Pacific Northwest, the maximum technical potential is approximately 18%. This lower value is due to the fact that approximately 69% of the nameplate generation capacity in the Pacific Northwest is produced by hydro-electric power plants [2]. Since the water in the river network has already been allocated, there is effectively no additional generation from hydro-electric plants for charging PHEVs. Therefore, the marginal generation is contributed by coal and natural gas plants, which only make up approximately 29% of the total generation [2].

A PHEV is a vehicle that has the ability to be propelled by either an internal combustion (IC) engine or electric motors powered by onboard batteries. Unlike a traditional hybrid vehicle, a PHEV has the ability to drive typical daily driving distances in an electric-only mode [3] when supplied with a correctly sized battery. Currently there are still significant uncertainties as to how automotive manufacturers of future PHEVs will select a control strategy for dispatching the IC and electric motor during a typical driving cycle. But based on existing conversion vehicles (i.e., hybrid electric vehicles converted to PHEVs) it can be inferred that the battery will be sized to allow for an electric-only mode enabling a 16-65 km range, which is well within the average daily distance of the average driver [3].

Using the average daily driving distances of 53 km (33 miles) and energy requirements published by the Electric Power Research Institute (EPRI) for various classes of vehicle, we chose a battery size that would provide 10 kWh for storage for the daily driving [4]. The energy required to charge this battery would be similar to the daily energy usage of a typical electric water heater.

Charging a PHEV is assumed to be performed at residential buildings via a standard wall receptacle. The charging can either be managed to minimize the impact on the distribution system, or simply circuit limited allowing maximal convenience to the consumer. Actively managing the PHEV charging could introduce the PHEV as an off-peak load to the electric system. While the majority of charging will be performed at night during the off-peak period, it is understood that there may be occasions of "opportunity charging" when consumers will desire to charge their batteries during times that are not off-peak, and possibly on-peak. When the battery charging is unmanaged, it may occur coincident with the native system peak and, thus, it is likely to have a larger impact on the system adding to the system peak.

In order to determine the impacts of adding PHEVs to

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distribution systems it is first necessary to have accurate models of the distribution system feeders and consumer load profiles. To accomplish this, Pacific Northwest National Laboratory (PNNL) collaborated with electric utilities in Washington State to obtain detailed feeder models and load profiles. Using actual feeder information and assumed PHEV charging profiles [6], the impact of various levels of PHEV penetration to the primary distribution system are evaluated on the *existing* infrastructure. Secondary system wiring ampacity, transformer capacity, and voltage support was neglected and the emphasis was placed on current capacity of the primary system. Analysis was performed using the SynerGEE® analysis tool from Advantica's Stoner Software [5].

This paper is divided into four additional sections. Section II discusses the assumptions that are made regarding the PHEVs and distribution system loads. Two case studies based on the assumptions of Section II are presented in Section III and Section IV discusses the cost impacts of the results as well as utility concerns. Section V presents the final conclusions of this paper.

II. PHEV ASSUMPTIONS AND LOAD PROFILES

Currently there are very few functional PHEVs in the U.S., most of which are in the research phase. Since the technology has not been commercialized there is no solid data on exactly how the consumers will utilize this new technology. For this reason it is necessary to make assumptions about how consumers are expected to charge their PHEVs.

In contrast, the existing consumer demand on distribution feeders is well known to the utilities that operate the feeders. Sometimes this information is inferred from measurements taken at the sub-station and other times the information is collected via Advanced Meter Infrastructure (AMI) from individual customer meter readings. While data collected via AMI is the preferred source of data, often times it not available.

A. PHEV Load Profiles

A battery size sufficient to provide an effective 10 kWh of storage was assumed for this analysis. The battery is also assumed to undergo a full charge/discharge cycle once a day. Currently there are two feasible voltages for charging PHEVs at residential locations, 120V and 240V. It will also be assumed that PHEV charging only occurs at single family homes; multi-family dwellings were excluded because of the uncertainty of available power supply for recharging the PHEVs, at least in the near-term.

For the 120V charging it is assumed that a standard 15A circuit would be sufficient and that no additional modifications to the residence would be necessary, i.e. zero cost. For the 240V charging, it is assumed that single family homes would already have a 240V receptacle in the garage or one would be installed at a cost to the consumer. In both the 120V and 240V charging scenarios, the battery charging equipment is assumed to be 87% efficient [1], resulting in 11.49 kWh of energy delivered to the home in order to provide a full charge to a 10 kWh PHEV battery.

Fig. 1 shows the distribution function for the charging profile that was assumed for the 120V smart-charging analysis. This charging profile was obtained from [6]. The obtained profile was then increased to account for the losses in the battery charging equipment. The profile of Fig. 1 is based on the assertion that there is some form of "smart-charging" technology that prevents the PHEVs from immediately charging at the maximum rate when connected to the residential receptacle.

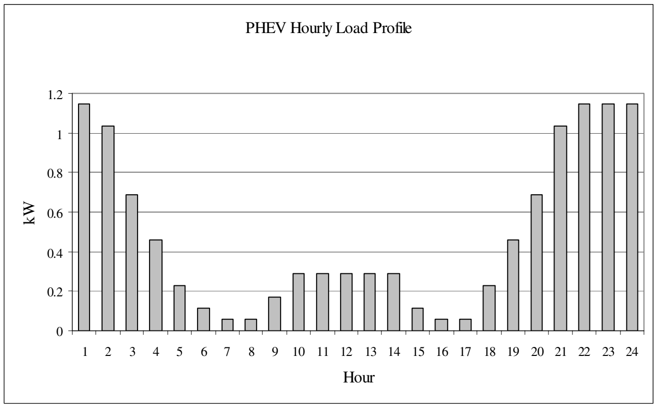

Fig. 1. Typical 120V/15A Smart-Charging Profile for a PHEV based on [6]

Since the charging profile of Fig. 1 is a distribution density function and not an individual charging profile it allows for charging at all times of the day, even during the peak load demand. Charging at other than off-peak times is attributed to opportunity charging in the mornings and evenings, with a small peak during the mid-day lunch period. The majority of the charging will occur during the off-peak period at night when people are at home. In this analysis there has been no allowance for opportunity charging in a commercial or industrial setting, all battery charging is performed in the residential sector. One significant factor to note from Fig. 1 is that when using the charging profile of Fig. 1, the maximum power consumed for battery charging is approximately 1.15 kW, which is less power than is required to run a typical hair dryer or space heater.

Fig. 2 shows the distribution function charging profile that was used for the 240V rapid-charging analysis. In this charging profile it is assumed that system-wide, all of the charging is performed within a 3 hour period directly after people arrive home from work. In this particular instance the load is nearly coincident with the existing peak system load. The charging profile of Fig. 2 does not contain any smart charging equipment. It is assumed that as soon as the consumer returns home the PHEV begins charging at the maximum possible rate until fully recharged. The higher voltage level coupled with the lack of smart charging technology results in a high impact scenario. In the charging profile of Fig. 2, the peak power consumed is 3.8 kW, which is comparable to a large household device such as a hot water heater.

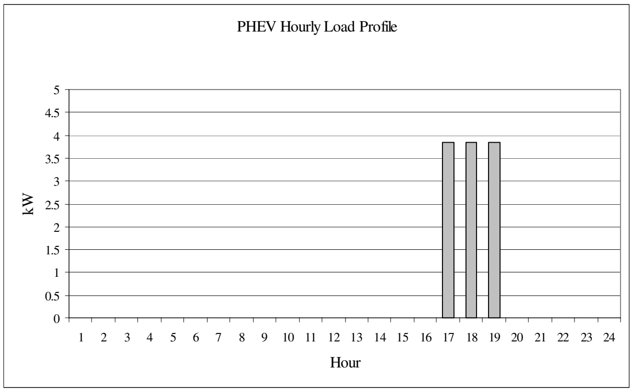

Fig. 2. Typical 240V/50A Rapid-Charging Profile for a PHEV

Actual individual demand per PHEV could approach the 11.49 kW needed to fully charge the battery in an hour, but is not seen in this study due to the choice of using distribution density functions. Furthermore, it is possible to have multiple residences on a single transformer charging at the maximum rate, at the same time. The issue of localized coincidental loads could have significant additional consequences on the secondary distribution system and will be addressed in future work.

B. Native Load Profiles

Since it has been assumed that PHEV charging will only occur at single family homes, the residential load profile will have the most significant impact on the analysis. For the purposes of this study there were two different residential load profiles that were used, one for the Western Pacific Northwest and one for the Eastern Pacific Northwest, shown respectively in Fig. 3 and Fig. 4. The load profile of Fig. 3 and Fig. 4 represent the energy consumed at the point of interconnection and do not account for distribution system losses.

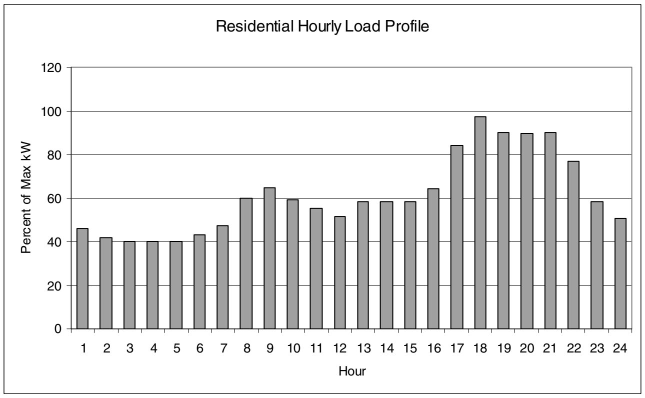

Fig. 3. Winter Residential Load profile for Western Pacific Northwest

III. CASE STUDIES

In the Pacific Northwest there are two distinct climate regions, the high precipitation western region and the arid eastern region. The western region is further characterized by a mild climate while the eastern region experiences significantly wider variations in seasonal temperatures. These two regions are separated by the Cascade mountain range which causes the significant climate differences. Because of the two drastically different climates, there are differences in the way distribution feeders are designed as well as in the load composition and behavior. For these reasons, separate evaluations of the impacts of PHEVs must be performed for each region.

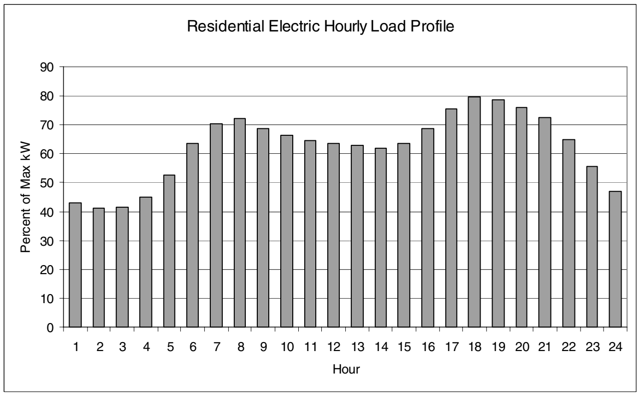

Fig. 4. Winter Residential Load profile for Eastern Pacific Northwest

A. Methodology

For each of the two regions SynerGEE® was used to perform load-flow studies. Rather than performing a typical peak load-flow study, hour-by-hour studies were performed. A simple peak study would not have fully characterized the PHEV impact on the distribution system due to the non-coincidental nature of PHEV and traditional loads.

PHEV loads were placed onto a line section within the feeder models based on the connected transformer kVA. The ratio of customers per transformer kVA was reached through discussions with each individual utility and their typical system design specification of kVA per house. The PHEV loads were then placed onto each section of line occupied by a residential customer in quantities equal to the desired penetration level. Using these new loads, the existing loads, hourly PHEV charging profiles, and hourly customer load profiles, an hour-by-hour power flow was performed for a full 24-hour typical weekday peak. The ability of a feeder to handle the additional load was determined by whether any elements of the feeder were overloaded or if there were any voltage violations.

For Figures 5-8, the penetration of PHEVs is given as the average number of PHEVs per residential household. These values are used since it is convenient to express the penetration as a fraction of PHEVs per household. In order to correlate the results of Fig. 5-8 with the 18% technical potential that was identified in [1] it is necessary to determine the average number of vehicles per single family residence in the Pacific Northwest.

Based on the total number of approximately 5 Million LDV vehicles in Washington State as of 2001 [7], and subtracting the number of vehicles that are owned by fleet owners, nationally 6%, Washington State has approximately 4.7 million LDVs [8]. We assumed that early adopters of

PHEVs would recharge the vehicle only in single-family homes. Using historic data (2001) from the 6th Northwest Power Plan for single family homes it was determined that there were 2,030,000 single family residences (1,810,000 site-built, 220,000 manufactured) for Washington State [9]. Therefore, a penetration of 0.5 PHEVs per household, 50%, would equate to approximately 1.015 million PHEVs, or 21.6% of the Washington State LDV fleet. Table 1 indicates other significant penetration values.

Table 1. Comparison of PHEVs per Single Family Home to % of LDV Fleet for Washington State

PHEVs per House (%)	LDV Fleet (%)
10	4.3
25	10.8
50	21.6
100	43.2

B. Western Pacific Northwest Case

The western region of the Pacific Northwest is a winter peaking region with a mixture of electric and natural gas home heating. Currently there are very few residential air-conditioning loads. Fig. 3 shows the residential load profile that was used for this study; the profile was generated using utility supplied AMI data.

The Western region was traditionally dominated by electric heating until the early to mid 90's at which point natural gas began to be extensively used. Natural gas was not only put in newer homes but also retrofitted into older homes. As a result the load profile of Fig. 3 represents a combination of electric and gas heated homes.

Fig. 5 shows the total feeder load including losses, measured at the substation, for a predominately residential feeder in the eastern region with each PHEV using the charging profile of Fig. 1. Four curves are presented in Fig. 5: the base load profile with no PHEVs, 25% of households containing a single PHEV, 50% of households containing a single PHEV, and every household containing a single PHEV. From Table 1 it can be seen that these penetration levels correspond to 0%, 10.8%, 21.6%, and 43.2% of the LDV fleet respectively.

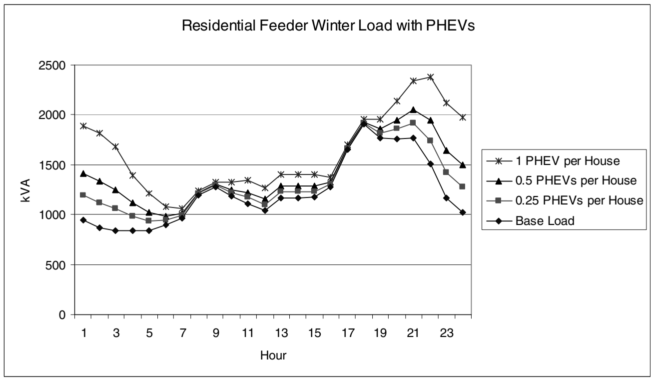

Fig. 5. Western Region feeder loading with 120V Smart-Charging

From curves of Fig. 5 it can be seen that when the charging profile of Fig. 1 is used there is no significant increase in the peak feeder load for 25% penetration and only a slight increase for a 50% penetration. As expected, the majority of additional energy is delivered in the off peak period, thus it is not coincidental with the native load profile. The feeder load profile shown in Fig. 5 gives an indication of the minimum impact that PHEVs could have on the system.

Fig. 6 shows the total feeder load including losses, measured at the substation, using the same feeder as in Fig. 5 with each PHEV using the charging profile of Fig. 2. As in Fig. 5 there are four curves, showing the same penetration levels, base loading, 25%, 50%, and 100%. In contrast to the previous case, nearly the entire amount of additional delivered energy is during the native peak load. The feeder load profile shown in Fig. 6 gives an indication of the maximum impact that PHEVs could have on the feeder.

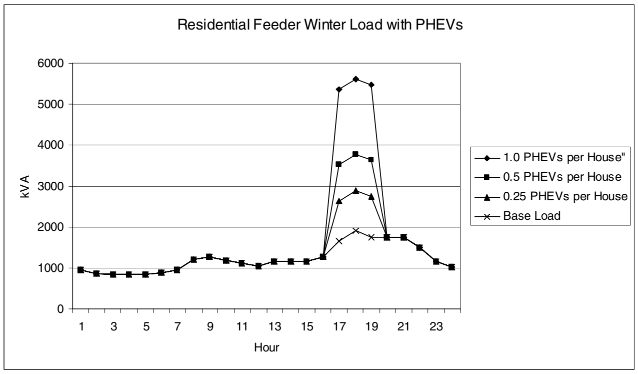

Fig. 6. Western Region feeder loading with 240V Rapid-Charging

All of the feeders examined in the western region were able to supply the additional energy required to charge a 50% penetration scenario using the profile of Fig. 1 without exceeding any equipment ratings. When the same penetration scenario was used in conjunction with the charging profile of Fig. 2 equipment rating limitations were rapidly encountered.

The results for the Western Pacific Northwest show that the existing distribution infrastructure could support the additional power delivery required for the 120V smart-charging profile of Fig. 1, even at penetration rates of 0.5 PHEV per house (1 PHEV for every other house), which for Washington State would equate to 21.6% of the LDV stock. However, equipment rating limits are expected to be exceeded with the 240V rapid-charging profile of Fig. 2.

C. Eastern Pacific Northwest Case

The eastern region of the Pacific Northwest is in general a winter peaking region with home heating being a mixture of electric, heat pumps, and natural gas. The vast majority of residential customers have home cooling either in the form of heat pumps or dedicated air-conditioning units. Because of the increased usage of heat pumps and air-conditioning units, Eastern Washington utilities generally have fewer customers connected to a transformer of a given kVA than in the

Western region.

The residential load profile in Fig. 4 was used to approximate the combined winter load profile of electric and gas heated homes. Actual measured values were unavailable from the utility, so the SynerGEE® default profiles were used. The utility supplying the feeder data agreed that this is a valid approximation of actual system conditions.

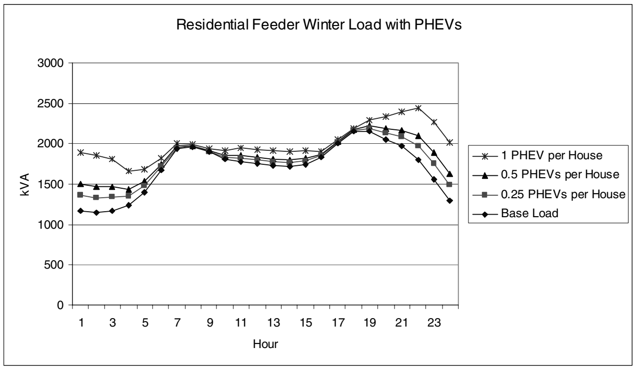

Fig. 7. Eastern Region 120V Smart-Charging

Fig. 7 and Fig. 8 show the total feeder load including losses, measured at the substation, for a predominately residential feeder in the eastern region with each PHEV using the 120V smart-charging and 240V rapid-charging scenarios. Examining the results at the substation level gives results that are similar to the Western Region; the existing distribution infrastructure can handle the additional power delivery required for the 120V smart-charging profile of Fig. 1, but would run into system limitations with the 240V rapid-charging profile of Fig. 2.

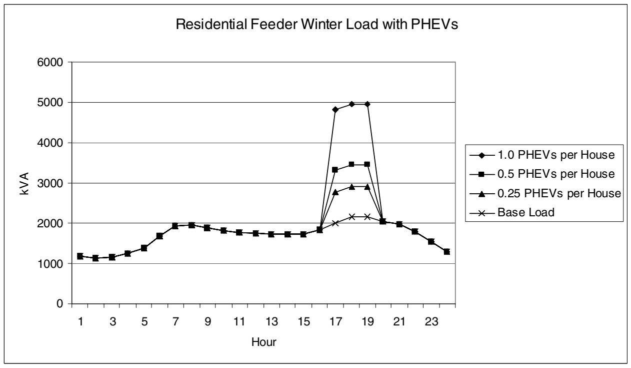

Fig. 8. Eastern Region 240V Rapid-Charging

D. Case Study Comparison

In both the western and eastern regions it was found that the 120V charging profile of Fig. 1 could be accommodated with the existing infrastructure, but the charging profile of Fig. 2 caused equipment violations.

The difference between the two regions is illustrated by the number of residential users connected to a single transformer. In the Western Pacific Northwest it is not uncommon to have 5-8 residential customers connected to a single 25 kVA transformer. In contrast, only 3-4 residential customers are connected to a single 25 kVA transformer in the Eastern Pacific Northwest. As stated in the previous section this difference is due primarily to the higher penetration of heat pumps and air conditioning units in the Eastern Pacific Northwest.

IV. COST OF CAPACITY REDUCTION/UTILITY CONCERNS

Addition of the PHEV load was examined using various assumptions and simplified models. In actuality, annual system load growth, voltage support, transformer capacity, secondary systems (secondary wiring, panels, and meters), and other unforeseen consequences will need to be addressed by the utility for this additional load growth. These issues may significantly affect utilities' planning and operations and result in increased capital costs.

Another issue that was not directly addressed in this study was the operational differences between utilities. Some utilities operationally limit feeder loading to 50% or 66% so that the load can be transferred to adjacent feeders if necessary, while other utilities allow feeders to be loaded closer to their physical limits. This issue was not directly addressed since this study was looking at the technical feasibility of the infrastructure to accommodate the additional load.

Additional studies will need to be completed in order to further identify and evaluate the above impacts to further address the concerns of the utilities.

V. CONCLUSIONS

The single most important conclusion from this study is that the existing distribution infrastructure in the Pacific Northwest is capable of supporting a 50% penetration of PHEVs with the 120V smart-charging profile, which equates to approximately 21.6% of the LDV fleet. This level of penetration exceeds the known capability of the existing generation resources, which is approximately 18% [1]. From the results of the 240V rapid-charging analysis, it is clear that for any significant level of penetration a "smart charging" device will be necessary to prevent the charging from occur on peak, otherwise the distribution feeders will become the limiting infrastructure.

This study assumed that there would be a significant penetration of PHEV on the existing infrastructure. In actuality it will take several years before PHEVs reach a significant penetration level, allowing utilities to adapt to the new load. If PHEVs are introduced onto distribution systems using smart charging technologies, over a reasonable timeframe, their impact should be manageable.

VI. ACKNOWLEDGMENT

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VIII. Biographies

Kevin Schneider (M’06) received his B.S. degree in Physics and his M.S. and Ph.D. degrees in Electrical Engineering from the University of Washington. His main areas of research are power system operations and infrastructure interdependencies. He is currently a research engineer at the Pacific Northwest National Laboratory (PNNL) in Richland, Washington. He is also an Adjunct Faculty member at the Washington State University Tri-Cities campus and a licensed Professional Engineer in Washington State.

Clint Gerkensmeyer (M'99) received the B.S.E. degree in Electrical Engineering from Arizona State University. Currently, he is a power systems research engineer with the Energy Science and Technology Division, Pacific Northwest National Laboratory, Richland, WA. Prior to joining PNNL, he was with Franklin County PUD No.1 and Bonneville Power Administration. He is a licensed Professional Engineer in the State of Washington.

Michael Kintner-Meyer (M’07) is a Staff Scientist at the Pacific Northwest National Laboratory (PNNL). He manages PNNL’s technology assessment of Plug-in Hybrid Electric Vehicle (PHEV) and their interactions with the grid. He is also managing and is intimately involved in the technology development of a smart charger technology for PHEVs. Dr. Kintner-Meyer has worked on various aspects of energy policy analysis and climate change policy for the Commission of European Communities, Danish Universities, the U.S. Department of Energy, and most recently is working with the Western Governors’ Association on electrification of the transportation sector including the assessment of PHEVs. Dr. Kintner-Meyer holds a recently issued patent on Electric Appliance Load Control and has authored communication standards for building automation (BACnet Standard). Dr. Kintner-Meyer received a Ph.D. in Mechanical Engineering from the University of Washington and a MS from the University of Aachen, Germany.

Robert H. Fletcher (M’79–SM’04) received the B.Sc., M.Sc., and Ph.D. degrees in electrical engineering from the University of Washington, Seattle. He is a Principal Engineer in System Planning and Protection with Snohomish County Public Utility District No.1, Everett, WA. He has over 38 years of electric utility industry experience as an Electrical Engineer. He is an author or co-author of several papers on the subject of distribution system efficiency and reliability. He is currently engaged in conservation voltage regulation and system efficiency research. He is Technical Chair of the Distribution System Efficiency Initiative (DSEI) conducted by the Northwest Energy Efficiency Alliance involving 20 electric utilities. Dr. Fletcher is a member of the IEEE PSACE Committee, RRPA Subcommittee, and Chair of the PSPI Distribution Planning WG. He is a registered Professional Engineer in the States of Washington and Oregon.