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Plug-in Electric Vehicle Infrastructure: A Foundation for Electrified Transportation

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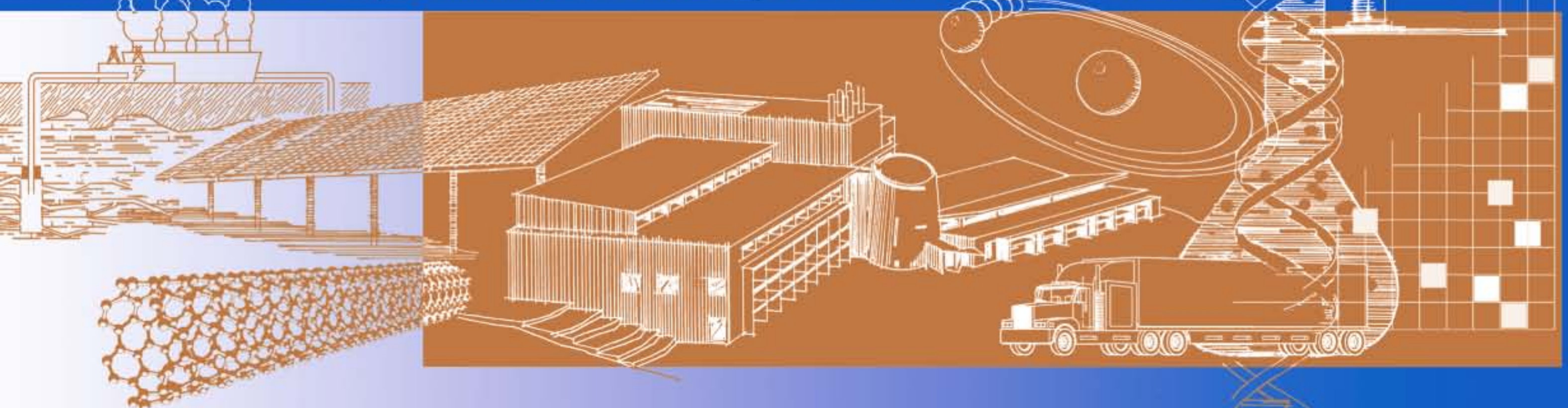

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Plug-in Electric Vehicle Infrastructure: A Foundation for Electrified Transportation

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Abstract

Plug-in electric vehicles (PEVs)—which include all-electric vehicles and plug-in hybrid electric vehicles—provide a new opportunity for reducing oil consumption by drawing power from the electric grid. To maximize the benefits of PEVs, the emerging PEV infrastructure—from battery manufacturing to communication and control between the vehicle and the grid—must provide access to clean electricity, satisfy stakeholder expectations, and ensure safety. Currently, codes and standards organizations are collaborating on a PEV infrastructure plan. Establishing a PEV infrastructure framework will create new opportunities for business and job development initiating the move toward electrified transportation. This paper summarizes the components of the PEV infrastructure, challenges and opportunities related to the design and deployment of the infrastructure, and the potential benefits.

Introduction

Over the last 100 years, oil has become the dominant transportation energy source. The technical performance, cost, and convenience of oil have yet to be challenged by alternative power sources. In the coming years, oil demand is expected to exceed supply, causing price volatility and supply disruptions. Burning oil also results in emission of greenhouse gases that contribute to climate change.

One way that nations could rapidly address the concerns caused by reliance on oil is to electrify the transportation system and expand the amount of electricity generated from renewable sources. The challenges to making the necessary technology and market transitions are significant but not insurmountable if complete implementation plans are created to account for the needs of various stakeholders. The U.S. Presidential Administration's goal is to invest in advanced technology supporting introduction of 0.5 million plug-in electric vehicles (PEVs) by 2015.

Research on plug-in hybrid electric vehicles (PHEVs) by the Electric Power Research Institute (EPRI) and the U.S. Department of Energy (DOE) in the late 1990s began as a result of electric vehicle (EV) introduction challenges (1). EV market growth was hampered by many factors, including battery performance and cost, long battery-recharge times, low oil prices, and consumer expectations. "Range anxiety," the fear of being stranded in an EV because of insufficient battery performance and accessible charging infrastructure, kept consumers away from EVs (2).

PHEV technology builds upon hybrid electric vehicle (HEV) technology experience. A PHEV's battery capacity is 5–10 times larger than an HEV's but less than 1/4–1/3 that of a typical EV (3). This reduces the cost of PHEVs compared with EVs while providing EV operation for short-range driving and HEV operation for long-range driving. Thus, PHEVs offer fuel savings, flexibility, and extended driving range to consumers.

Because of the relatively small PHEV battery, initial expectations were that PHEVs would be charged at home from typical 120V outlets. However, since starting initial investigations of PHEV technology, the PHEV infrastructure scenarios have expanded significantly.

In parallel with PHEV development, states have moved toward rapid renewable energy expansion. Twenty-four states have adopted mandatory renewable energy standards, while five have adopted voluntary standards (4). The variability of renewable energy generation creates integration challenges (5, 6). PEVs represent a new, flexible electricity load, which could enable expanded renewable energy generation.

Infrastructure to enable safe, efficient PEV charging and charge management has evolved rapidly in recent years. This paper summarizes the components of the PEV infrastructure as well as challenges and opportunities.

Discussion

It may seem simple to “just plug in” PEVs. However, for the PEV market to expand, a broad infrastructure plan is being developed to deliver consumer value and satisfaction. Effective infrastructure enables greater use of the battery technology, as shown in (7), where recharging throughout the day provided approximately 10% greater fuel savings using 50% less battery capacity. Fully using these resources depends on the following PEV infrastructure components, which are discussed in the subsequent sections:

- Energy Storage
- Charger – On-board/Off-board
- Cords and Connectors
- Electric Vehicle Supply Equipment
- Advanced Meters
- Home Area Networks
- Parking Lots and Neighborhoods
- Buildings/Multi-unit Dwellings
- Smart Grid
- Aggregation Algorithms
- Distributed Generation/Storage
- Renewable Generation
- Communications Architecture
- Information Technology

Energy Storage

With energy storage, grid electricity is stored on-board the vehicle. Energy storage combined with lightweight vehicle design and efficient motors, creates a competitive alternative to conventional vehicles. Lithium-ion battery technology is the likely energy-storage candidate for near-term vehicles.

The DOE Energy Storage program collaborates with industry to address life, cost, and safety challenges of energy storage (8). Energy storage life is affected by cycling routines and ambient storage conditions. Cost is affected by materials and manufacturing methods and volumes. Safety is affected by design, chemistry, and manufacturing methods.

Energy storage is an enabler of electrified transportation and international competition for energy-storage market share will emerge. The best use of limited supply of batteries must be investigated. Dedicating a large battery for a vehicle used less than one hour per day for personal travel may limit potential benefits. Large batteries could provide additional value, e.g., by providing grid services in or out of a vehicle. There is opportunity in analyzing the battery capabilities, potential value, and ownership scenarios.

Charger – On-board/Off-board

The power electronics for charging the energy storage system could be on-board or off-board the vehicle. Improving the efficiency and cost of this component may be critical to the success of electrified transportation. Weight of on-board units is also important. On-board units take AC power from the grid and rectify it to DC power to charge the DC battery pack. Off-board units make this same conversion and deliver DC power to the vehicle. Communication between the battery management system and the charger must occur to ensure energy is delivered safely. Power-quality standards for chargers are being developed with the goal of minimizing detrimental impacts to grid operation.

Vehicle charging also offers the opportunity to reverse power flow from the vehicle battery to the grid. The value of this function must be balanced with the inefficiency and battery-life impacts of reverse power flow.

Chargers and associated cords are categorized by voltage and power levels: Level I is 120V AC up to 20A (2.4kW), Level II is 240V AC up to 80A (19.2kW), and Level III (which is yet to be defined fully) will likely be 240V AC and greater at power levels of 20–250kW (9). It is expected that similar definitions will be created to categorize charging with DC power delivery. The value of each charge power level is tied directly to the size of the on-board battery pack and the time available for recharging.

Cords and Connectors

In the previous generation of EVs, cords and connectors became a point of debate and made introduction challenging. Today, SAE has led efforts to standardize a connector for conductive charging in the United States. The SAE J1772 standard defines a five-pin configuration that will be used for Level I and Level II charging (9). A Level III connector and the use of the current connector for DC power flow are under development. Tripping hazards due to cords in garage areas and public places may be a safety and adoption hurdle.

Electric Vehicle Supply Equipment

Electric vehicle supply equipment (EVSE) improves the safety of vehicle charging in accordance with the National Electric Code (NEC). The EVSE enables power flow between the electricity distribution system and the PEV only when a cord and connector are completely connected. For Level II charging, the cord is permanently attached to the EVSE and is de-energized when not connected to the vehicle inlet. The EVSE and charger may be a single component if the charger is located off-board the vehicle. In some regions, the EVSE will be attached to or include a sub-meter for measuring electricity delivered to the vehicle separate from electricity delivered to the rest of the premise. This feature supports low-carbon fuel standard accounting.

The installation of an EVSE in a building may present a significant hurdle to adoption because it involves multiple parties, including utilities, building inspectors, electricians, and vendors (12). The time from purchase to functioning installation might be as much as 30 days in some regions providing a less than ideal experience for consumers. Related codes and standards efforts are discussed below.

Advanced Meters

Investment by utilities and governments in smart-grid technology supports the improvement of utility operations. Advanced meters are likely to be the primary access point for utilities to gather information on consumer use and transmit information to consumers to alter their behavior. Advanced meters are not required to enable vehicle charging or charge management. However, future PEVs may be the most significant configurable load accessed by advanced meters.

Home Area Networks

Home area networks enable consumers to collect information on and manage the operation of their homes. The PEV, EVSE, sub-meter, and the advanced meter could be integrated into the home area network along with appliances, lighting, and heating and cooling systems. The home area network is likely to be a primary point of information access for consumers. Adoption rates are uncertain.

Parking Lots and Neighborhoods

It is expected that most PEV charging will take place in or near a primary residence. Charging in workplace parking lots is likely to provide the next greatest opportunity for oil displacement (10). Several studies compare the cost of infrastructure (11, 12). A critical challenge related to charging outside the home is managing multi-party use of infrastructure providing greatest cost-benefit ratio to the infrastructure owner/operator. Infrastructure planning methods along with measurement and billing functions need investigation. Algorithms for managing shared resources in neighborhoods and parking lots may be needed as markets develop. Previously, analyses showed the ability of generation systems to accommodate large populations of vehicles with at least some ability to shape the energy demands (15-18). Current analyses focus on the impacts on neighborhood distribution systems (19-24). Critical issues include overheating of transformers due to increased loads and coincidence of loads and imbalances in the three-phase system. As has been the case with HEVs, select neighborhoods are likely to see much higher than average PEV densities and potential overloading. Multiple vehicles on a single phase of a three-phase distribution system could cause phase-to-phase imbalances resulting in induced magnetic fields that may affect the surroundings. Utility planning and operational data analysis could be used to prevent problems.

Buildings/Multi-unit Dwellings

The strength of the relationship between PEVs and buildings are situational. For residential areas, home area networks and advanced meters should enable significant integration. In commercial and public areas, Leadership in Energy and Environmental Design (LEED) building certifications assign value to the use of alternative fuel vehicles. PEV loads may need to be managed to avoid increases in peak demand charges. Innovative solutions may exist to integrate vehicle services (charge and discharge), building load management, and renewable energy generation to optimize total cost savings and value delivery. A significant challenge will be planning and coordinating access to charging resources. Waiting for access will be unacceptable for PEV customers and non-PEV customers are likely to be irritated by unoccupied but reserved parking locations. Installation, access, billing, and management of vehicle charging in dense residential/commercial areas are challenges to be resolved.

Smart Grid

Smart grid technologies open a new door for system optimization. The smart grid allows utilities to better understand their needs and resources and optimize system use. Various levels of implementation likely will exist, from data monitoring and remote controls throughout the entire network to basic automation of meter reading. Although smart grid implementations may vary regionally, this technology may enable vehicles to roam from one utility network to another if basic interoperability standards are adopted across broad regions. The smart grid may also enable integrating greater levels of renewable energy resources by combining generation data with load-management potentials and resource planning.

Aggregation Algorithms

Aggregation services collect a diverse or common set of vehicle loads to create a more desirable load. This is a new and evolving area. Research by the National Renewable Energy Laboratory, Xcel Energy, and Gridpoint (formerly V2Green) demonstrated initial aggregation algorithms in field tests (14). Denholm and Sioshansi analyzed vehicle fleets in the Electric Reliability Council of Texas (ERCOT) region under utility management in aggregate, highlighting the fuel savings and emissions benefits (25). Others, including Enernoc and the MAGIC Consortium, have begun to explore aggregation of loads and sources to provide grid services. Aggregation algorithms will be refined as operational data is collected. A recent report by ISO/RTO Council highlights aggregation of vehicle loads as a necessary step to enter nearly all grid service markets, which would extend the value of the vehicles beyond just oil displacement (26). Proliferation of aggregation may be highly dependent on consumer monetary or perceived value. Aggregation of diverse loads provides the flexibility necessary to deliver perceived value of dedicated "green" energy supplies to vehicles.

Distributed Generation/Storage

Distributed storage systems that dynamically aggregate and filter a collection of loads—such that the collected load is smooth, consistent, and repeatable—aid in the efficient and cost-effective delivery of electricity. Electrochemical energy-storage technologies, such as PEV batteries, have not yet been cost effective for grid applications. Market expansion could benefit vehicle and grid operations if common energy-storage attributes are identified so that production volumes could be increased. The work of American Electric Power (AEP) on community energy storage and Southern California Edison (SCE) on the “garage of the future” are consistent with developing complementary markets for energy storage in mobile and stationary applications (27, 28).

Renewable Generation

The variability of renewable electricity generation is managed in multiple ways, including geographic diversity, computer forecasting, operational controls, and planned flexible resources. Renewable generation variability has integration costs (5, 6, 29). Experience suggests that wind generation will be greater in the evenings and at high penetrations it conflicts with minimum output levels of fossil power plants. A significant amount of energy for PEVs will be needed at night, which helps address wind energy integration challenges. The response time of batteries and chargers to load-management commands should be much less than one minute, which is faster than nearly all flexible resources in the grid today. State Renewable Portfolio Standards set goals for renewable integration, and the parallels between these standards and vehicle introductions is an area meriting further study.

Communications Architecture

Communications architecture has been a strong component of economic growth in the US since the introduction of microprocessors in the 70’s (30). It is the physical backbone that enables business to function today. U.S. communications architecture provides the opportunity for PEVs to be an active participant in the future grid. SAE standards groups are developing the expectations and implementation methods to enable PEV communication. The information to be passed is critical while the physical means by which it is passed is less critical as long as interoperability is ensured. The need for security features will become more important as utilities base operational decisions on information transferred over communications networks.

Information Technology

Information technology is needed to manage the movement of data between parties and to transform these data into knowledge and decisions. The computational power needed to manage the Smart Grid to its fullest extent has yet to be determined. Creating a multilayered operational network using embedded systems may provide a robust, efficient, flexible, responsive system relative to the centrally managed approach used today.

Future Scenarios

The infrastructure components discussed above summarize the status and potential of near-term PEV implementation. These components could be integrated with additional scenarios. Lightweighting of PEV systems could optimize the use of a limited supply of energy-storage technology (30). Intelligent transportation networks with roadway-to-vehicle and vehicle-to-vehicle communication may reduce congestion and increase safety. Plentiful and simple vehicle-charging infrastructure supports the evolution of car sharing and enables smooth transitions between multi-modal systems. Other scenarios include roadway power delivery (32) and wireless power delivery (33).

System Integration and Interoperability

Interoperability of PEV infrastructure components is critical for widespread deployment of PEVs thus enabling new businesses and jobs. Multiple standards entities are focusing on developing codes and standards supporting PEVs and grid integration. Blake et. al. summarize codes and standards associated with alternative fuel vehicles (34), and (12, 26) summarize standards related to grid integration and future service options. Select standards activities related to infrastructure are discussed below.

In the United States, SAE is creating standards defining the connection points and interoperability of PEVs with the rest of the infrastructure. SAE J1772 defines the standard connector to be used between the PEV and infrastructure for conductive power delivery. SAE J2836 defines usage scenarios of PEVs with utility programs and J2847 defines the communication message content and structure between PEVs and the grid. Together these create a basis for interoperability. SAE J2894 is being developed to define power-quality requirements for chargers.

Standards and testing organizations—including the National Institute of Standards and Technology, Underwriters Laboratories, and National Fire Protection Agency—are collaborating to define grid safety and integration methods. IEEE has developed IEEE 1547, and is working on P2030, to define interoperability for distributed generation and loads along with communication standards between these components and the Smart Grid. EPRI's Infrastructure Working Council facilitates coordination among industry, government, and standard groups.

In Europe, the International Electrotechnical Commission (IEC) and International Organization for Standardization (ISO) bodies lead the development of standards for PEVs. In Japan, the Japan Automobile Research Institute (JARI) is developing guidelines and standards for integration of vehicles. The development of worldwide standards for connectors, operational scenarios, and information transfer would be beneficial. Coordination with international entities is a high priority for DOE. The most significant challenge related to codes and standards is the coordination of activities across multiple standards bodies and industries.

Roaming

"Roaming" of PEVs is important for building consumer satisfaction and confidence. With more than 3,000 U.S. utilities, consumers likely will interface with multiple utilities when charging PEVs outside their homes. The costs and options for charging at home versus roaming may vary significantly. There are parallels with the early introduction of mobile phones. When roaming, consumers encountered high costs and service frustrations until the network and contractual relationships evolved. Although it may be less significant for PHEVs, which have an ICE for extended driving and will get charged most often at home, market introduction of PEVs in general could be hampered by roaming problems.

Infrastructure Challenges and Opportunities

Many of the challenges to PEV infrastructure are presented above. The primary challenge is component interoperability within the system, which standards bodies are addressing. Coordination with international entities is another issue; successful coordination would lower the cost of market expansion by providing manufacturers with greater volumes of consistent products.

Developing a PEV infrastructure also presents opportunities. Energy storage technology is the fundamental element needed for PEV market evolution. While high battery costs limit market penetration, identifying multi-value stream pathways for PEV energy storage is important. The parallel growth of renewable energy provides new integration opportunities for flexible resources. PEVs may be a suitable flexible resource because of their fast response and broad window of opportunity for charging. Charging patterns will depend on consumer behavior, which can be assessed and influenced via the smart grid and predictive-behavior tools.

Finally, there is opportunity to determine how CO_2- and oil-displacement credits will be allocated to PEVs; this topic is not covered adequately in the current literature. Sub-metering efforts in California are establishing the data-collection methods for verifying electrical energy delivery and consumption by vehicles. An NRDC/EPRI (35) report highlights the relative CO_2 impacts of the source of electricity used for PEVs. Although the energy delivered to a PEV may not have been generated directly by a renewable source, if its flexibility in operation enables expansion of renewable sources at a lower cost of integration, then there is a substantial CO_2 impact.

Conclusion

The confluence of battery technology developments, oil prices and price volatility, renewable generation and integration technology, and environmental concerns is uniting government and industry behind a transition to a transportation system that does not depend on oil. PEV infrastructure will transform how energy is delivered to vehicles. The infrastructure to support the introduction of PEVs is much more complex than an extension cord and outlet as previously assumed. PEVs will connect to the new transportation system through many, yet-to-be-developed infrastructure components forming a foundation for an electrified transportation system. Interoperability of these components is a core role of DOE, national laboratories, industry, and standards organizations. International collaboration should accelerate market expansion. The challenge to develop a robust, flexible, renewable, low-cost system for vehicle energy delivery while providing confidence, comfort, and value to the consumer will form the core of research programs over the coming years.

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