PHEVs and BEVs in Coupled Power and Transportation Systems

Glossary BEV Battery electric vehicle. - DSM Demand side Management; utility-sponsored programs to influence the time of use and amount of energy use by select customers. - G2V Grid-to-vehicle; using the electrical grid to charge the battery of a vehicle. - HEV Hybrid electric vehicle. - OM Outage management; set of manual and/or automated procedures used by operators of electric distribution systems to assist in restoration of power. - PHEV Plug-in hybrid electric vehicle. - V2B Vehicle-to-building; exporting electrical power from a vehicle battery into a building. - V2G Vehicle-to-grid; exporting electrical power from a vehicle battery to the electrical grid.

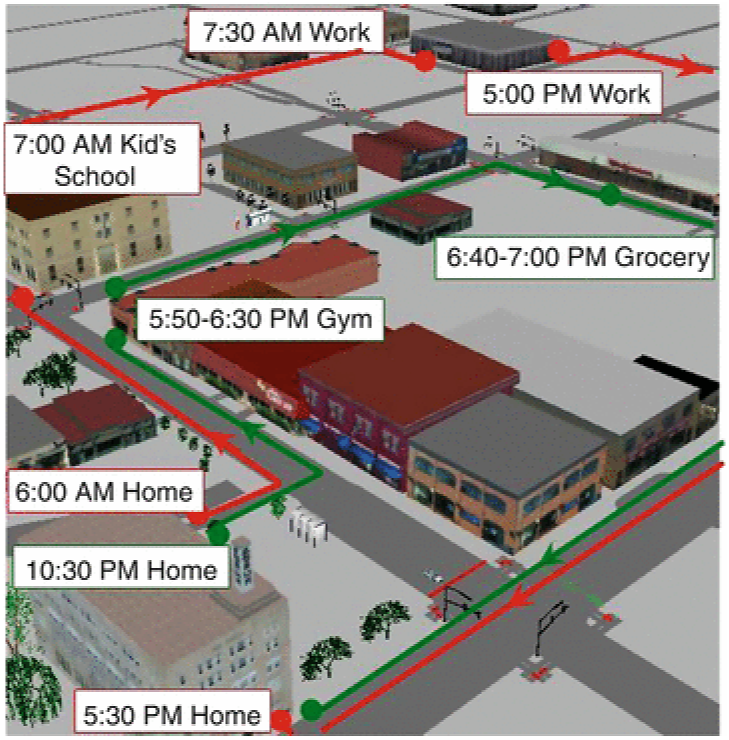
Definition

With the price of oil peaking in the recent past close to the once unimaginable $150 per barrel and the threat of global climate change increasingly acknowledged, the transportation sector is employing a number of new technologies that will enhance energy security by reducing the current dependency on oil-based fuels. Should the gasoline cost increase in the future, Plug-in Hybrid Electric Vehicles (PHEVs) and Battery Electric Vehicles (BEVs) will become the economical choice for transportation. Widespread adoption of PHEVs/BEVs will also improve air quality and carbon footprint, since point source pollution is easier to control than mobile source pollution. This level of control is essential for effective implementation of carbon cap-and-trade markets, which should spur further innovation. In USA, sales of Hybrid Electric Vehicles (HEVs) have grown 80% each year since 2000, proving that PHEVs/BEVs are likely an eventual reality that must be dealt with [1]. The implications of this reality will be highly dependent on the policies in place to use PHEVs/BEVs to the benefit of the transportation and power systems, as well as the drivers, industry, and public at large.

Beyond fuel costs and sustainability , the primary concern of the transportation sector is congestion. In 2005, congestion was estimated to cost the US economy $78.2 billion in wasted time and fuel [2]. If PHEV/BEV drivers are given appropriate incentives (e.g., strategically placed energy exchange stations), traveler behavior (e.g., choice of routing, departure time, and destination) impacting congestion may be affected.

In addition, the power industry is currently challenged to maintain reliability of operation while expanding the grid to meet growing demand. Large blackout such as the northeastern one in 2003 may create loses in billions of dollars [3]. Introducing the renewable resources to meet growing demand requires energy storage to deal with interfacing [4]. If proper policy is in place PHEVs/BEVs can provide a promising solution acting as mobile decentralized storage (MDS) of electrical energy . In this capacity, PHEVs/BEVs can serve in two modes: grid-to-vehicle (G2V) and vehicle-to-grid (V2G), each providing benefits to the power system operation. The G2V mode can be used to charge PHEVs/BEVs at reduced cost when the power system load is reduced and generation capacity is abundant, such as during night time. The V2G mode may be used when demand is high or supply is accidentally lost since the stored electric energy can be released from PHEVs/BEVs in an aggregated way, which will offer major contributions to regulation service and spinning reserves, as well as load-shedding prevention. The mobility of the energy storage in PHEVs/BEVs allows for strategic placement of the distributed generation source to optimize power system needs.

Figure 1 illustrates the spatial and temporal coupling of the power and transportation systems through showing an example of a PHEV/BEV driver's route, highlighting destinations where the driver could potentially engage in G2V or V2G activity. Options for meeting selected criteria for electricity and transportation networks simultaneously are numerous. Developing policy strategy requires understanding of trade-offs involved in pursuing certain solutions at the expense of others. The all-encompassing theoretical framework for such studies to the best of our knowledge is not available.

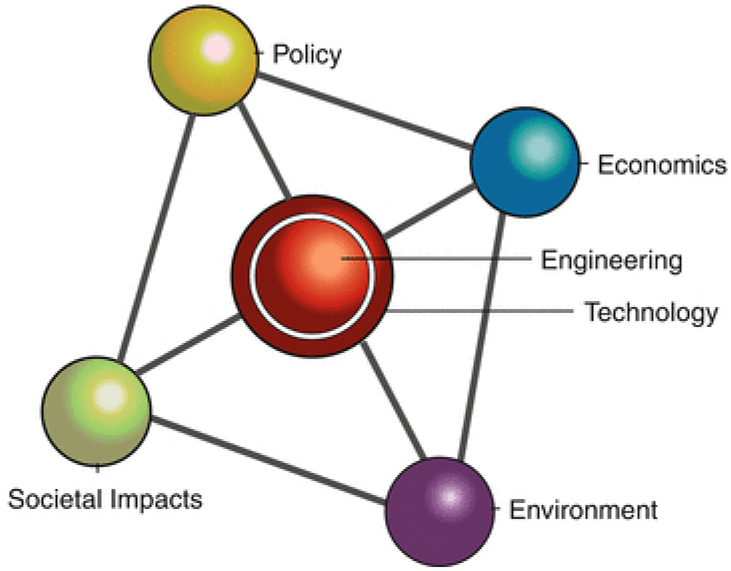


PHEVs and BEVs in Coupled Power and Transportation Systems. Figure 1 Temporal and spatial dimensions of plug-in opportunities

Traditionally, scientists have adopted a divide and conquer approach to understanding complex phenomena. Unfortunately, systems with emergent dynamics that are dominated by contextual interactions are not well suited to this classical approach (e.g., [5-7]). In such cases, directly addressing the couplings of system components may actually hasten progress. While this linkage presents new opportunities to improve the functioning and capacity utilization of each system, it also raises the spectrum of increasing dynamic complexity and cascading failures across systems.
In this entry, several open policies and research goals will be discussed, which facilitate optimizing the integration of the transportation systems and the behavior of its travelers with the electricity systems and behavior of its end-customers. PHEVs/BEVs based demand side management (DSM) and outage management (OM) are also presented as an application of PHEVs/BEVs using in the coupled power and transport system.

Introduction

The impacts PHEVs/BEVs will have on transportation systems, power systems, and air quality are very complex. Studies conducted to date on this topic make many assumptions to simplify the problem. As stated in the definition, the problem space must be treated as one large complex system in order to capture emergent behavior.
The complexity of the issues involved in studying PHEVs/BEVs and their interaction with electricity and transportation networks is shown in Fig. 2, where several disciplines that need to be involved in researching this multidisciplinary problem are shown.



PHEVs and BEVs in Coupled Power and Transportation Systems. Figure 2 Illustration of multidisciplinary nature of problem

Recent analyses confirm the feasibility of the grid-to-vehicle (G2V) and vehicle-to-grid (V2G) concepts [8-13]. The Electric Power Research Institute speculates that V2G could reduce the requirement for global, central-station generation capacity by up to 20% by the year 2050 [14]. Several studies omit any consideration of vehicle locations and desired activity patterns and assume a percentage of vehicles are plugged in and available when estimating the benefits to the grid and to drivers [8, 10, 11].

Many researchers have investigated the various potential benefits and implementation issues of the V2G concept. Kempton and Tomić studied the fundamentals of using PHEVs/BEVs for load leveling, regulation, reserve, and other purposes [15, 16]. Hadley and Tsvetkova analyzed the potential impacts of PHEVs on electricity demand, supply, generation, structure, prices, and associated emission levels in 2020 and 2030 in 13 regions specified by the North American Electric Reliability Corporation (NERC) [17]. Meliopoulos et al. considered the impacts of PHEVs/BEVs on electric power network components [18]. Anderson et al. performed the case studies of PHEVs/BEVs as regulating power providers in Sweden and Germany [19]. Guille and Gross presented a proposed framework to effectively integrate the aggregated battery electric vehicles into the grid as distributed energy resources [20]. The combined impact PHEVs/BEVs make on both electric power system and transportation network has not been explored as much. When considering the role of PHEVs/BEVs as dynamically configurable (mobile) energy storage, the potential impacts on both electricity and transportation networks may become quite diverse. The flow of traffic is an important factor in deciding the flow of electric power that could be utilized from PHEVs/BEVs. Correlating the movement of people to the movement of the power load offers new opportunities in the smart grid.

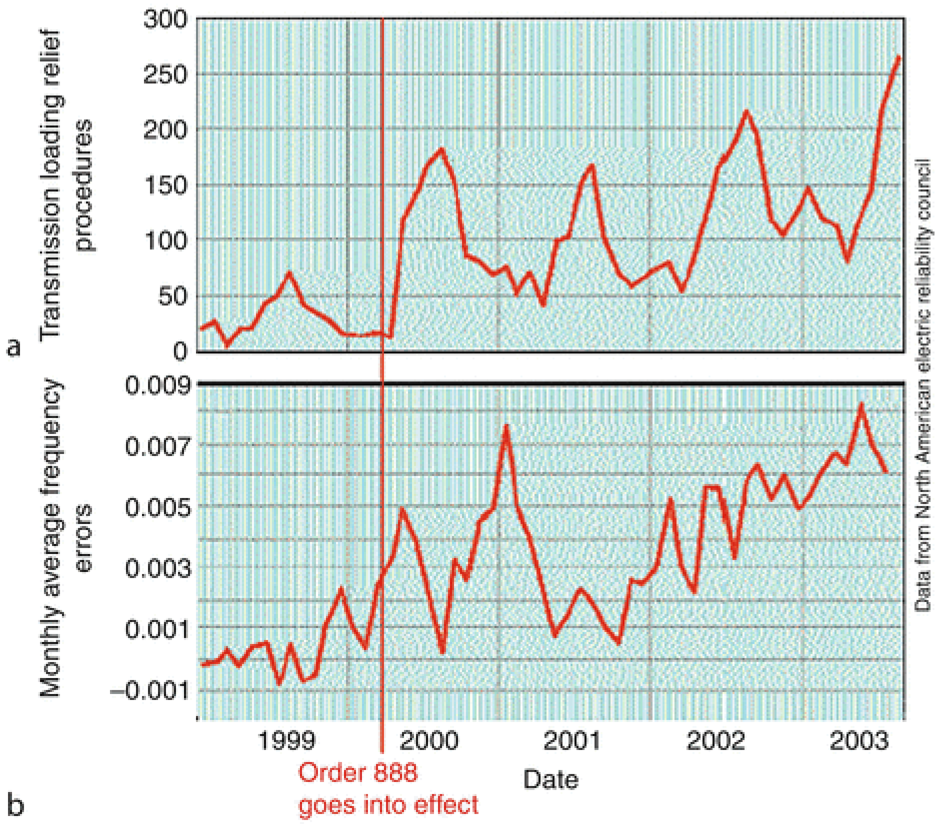
One of the major advantages of PHEVs/BEVs is their usefulness as an MDS . MDS is a revolutionary concept because currently the power grid has no storage except for 2.2% of its capacity in pumped storage [11]. Without significant and reliable storage of energy, maintaining grid stability and reliability under the growing electricity demand is a complex problem. Utilities may contract with others to provide power in any one of the four types of markets: base-load power, peak power, spinning reserves, and regulation services. Several studies have shown that PHEVs/BEVs can provide ancillary services (spinning and regulation) at a profit [8, 10, 11]. Spinning reserves receive payment for providing continuous capacity regardless of whether energy is provided, and receive further payment if called on to feed energy into the grid. Regulation services feed a nominal amount of energy into the grid, and receive payment for reducing or increasing their energy consumption as needed. In the case of PHEVs/BEVs, being plugged-in in a predictable way means that capacity is available to feed into the system if called upon. PHEVs/BEVs are particularly well suited for regulation services since the impact on vehicle's energy resources may be zero.

The pricing of V2G and G2V services is expected to cause a fundamental shift in the behavior of PHEVs/BEVs drivers. Further research is needed to investigate the exact nature of this shift; however, if the pricing schemes are developed with both the power system and transportation system in mind, then PHEVs/BEVs could help solve problems plaguing the traffic network, particularly congestion. The pricing scheme should also consider air quality impacts caused by charging at different times in the day. As mentioned earlier, MDS will allow for renewable energy to be used more efficiently. There will however remain times of the day more dominated by "dirty" fuels than others.

As observed, the body of research literature related to the multidimensional impact of PHEVs/BEVs is quite small. The remainder of this section will focus separately on the dual problems of improving the stability and reliability of the electrical grid and improving the efficiency of the roadway network.

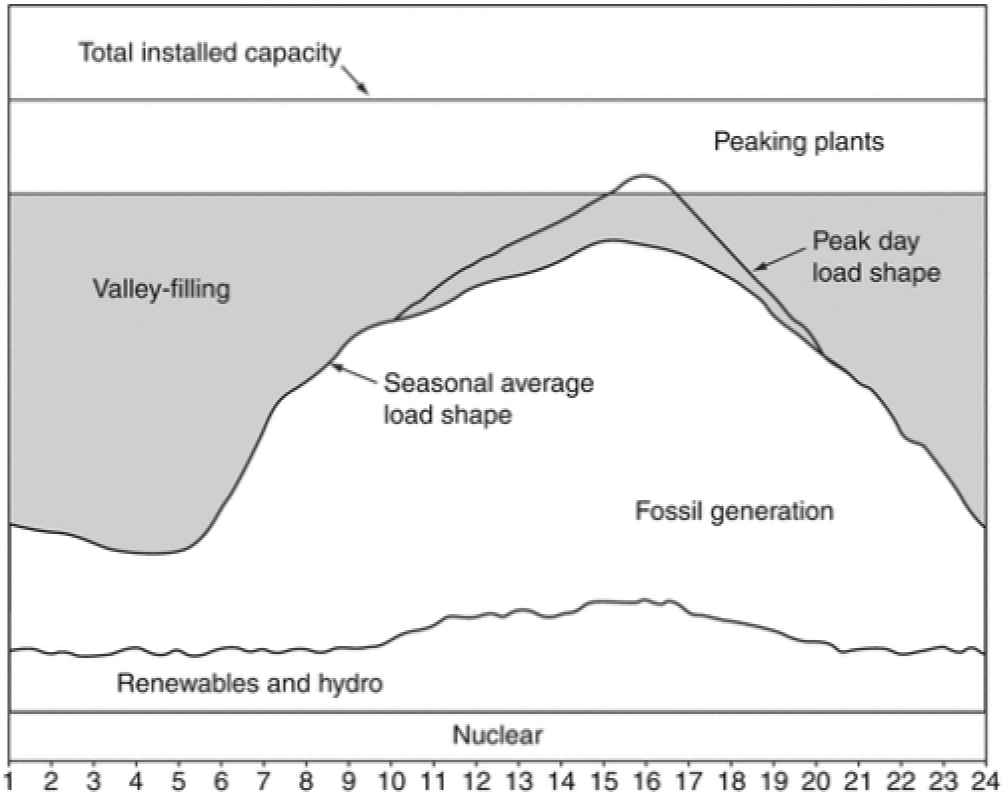
Stability and Reliability of the Electric Grid

Stability and reliability of the US electric grid have become issues of increasing concern since the occurrence of several blackouts in the 1990s (Western Interconnect in 1994 and 1996, and the Eastern Interconnect in 1999) and system deregulation. The devastating impact of the northeast blackout from August 14, 2003 reminded that the situation with the grid is only worsening and not improving. Here, a stable system is defined as one in which the phase and frequency of power generation units are constant. Ability of the system to maintain the state of equilibrium during normal and abnormal conditions is a measure of stability. Reliability is defined as the ability of the system to meet unexpected demand and respond to failures. Ability of the system to deliver electricity to customers within the accepted standards, which may be affected by the failure rate, repair rate, or duration of loss, is a measure of reliability. Figure 3 illustrates the worsening stability problem. Order 888 in Fig. 3 relates to the Open Access to Transmission issued by Federal Regulatory Commission in 1996, which is the result of an authorization passed by the Congress as a part of the Energy Policy Act of 1992.



PHEVs and BEVs in Coupled Power and Transportation Systems. Figure 3 Illustration of multidisciplinary nature of problem [21]

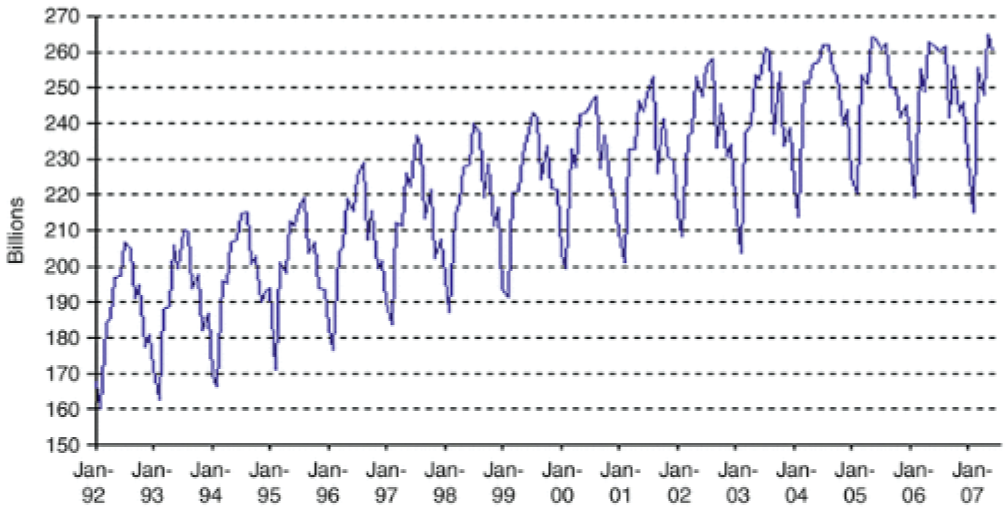
A major challenge in achieving these goals (stability and reliability) is the lack of energy storage. Figure 4 depicts the peaking structure of an example power load over the course of 1 day. In this example, demand grows rapidly starting at 6 a.m. and begins to decline after hitting a peak around 3 p.m. This peaking phenomenon is especially important to consider given that different energy sources are available at different times of day. For example, wind energy is most widely available at night when the demand for power is the lowest. While it may seem intuitive that a flat demand curve is the ideal, this is not necessarily true. More research is required to determine if parts of the system (e.g., transformers) require time to cool down. The large scale use of energy storage would significantly help meeting the stability and reliability needs, including managing the load variations shown in Fig. 4.



PHEVs and BEVs in Coupled Power and Transportation Systems. Figure 4 Illustrative peaking of electricity load [12]

Efficiency of the Roadway Network

Congestion is a problem not only in the electricity grid network, but also in the roadway network. Vehicle miles traveled (VMT) has risen consistently since the advent of the automobile, with dips when gasoline prices rise quickly (See Fig. 5 for the VMT trend since 1992). If the transportation sector is shifted to an alternative fuel source (i.e., electricity) with greater price stability, and especially if the source of the fuel is renewable, then VMT is expected to continue to increase into the foreseeable future. While mobility is an indicator of economic success, the expansion of a roadway system is limited by available space and finances. Roadway network efficiency is further constrained by the individual autonomy of drivers who act in their self-interest instead of the interest of the system (see [22] for a theoretical description of traveler behavior).



PHEVs and BEVs in Coupled Power and Transportation Systems. Figure 5 US highway VMT [23]

Extensive research has been conducted on improving the efficiency of the transportation system via methods such as pricing and technology, but few solutions proposed offer a case even close to being as comprehensive as PHEVs/BEVs.

Policy Issues

The policy issues presented here are centered on incentives to help industry develop and bring new value to end users of electricity and transportation networks , and society at large, while encouraging competition and development of new business opportunities.

Improve Electric Grid Performance

Widespread deployment of PHEVs/BEVs will allow for increased energy storage, and improved reliability and stability of the electric grid. Linking the transportation and power systems through PHEVs/BEVs will allow for electrical energy storage on a scale much larger than is currently feasible. The additional energy capacity will be directly proportional to the penetration of PHEVs/BEVs into the automobile market, and modeling (see the modeling section) is needed to determine the exact increase in capacity across the space and time dimensions.

The new mobile storage can only benefit the electric grid if it is available at the right time and place to service the grid when needed. To determine PHEVs/BEVs' demand for electric energy across space and time, travel patterns must be considered. Figure 1 shows an example of such a pattern, highlighting several destinations where a driver could potentially engage in G2V or V2G.

Stability and reliability issues were mentioned earlier. V2G is poised to greatly aid the grid in becoming more reliable and stable because vehicles are only in use for a small portion of each day (average daily travel time person in 2001 was 82.3 min [24]). During the remainder of the day, the vehicles can be plugged in and provide services (e.g., ancillary or regulatory).

This approach requires a policy shift to allow use of the MDS for energy to maintain stability and reliability. Also, policy that encourages utilities to cooperate with the PHEV/BEV owners or aggregators and provide tariff incentives for their participation in programs aimed at demand and distributed generation management and optimization is missing at the moment.

Enhance Penetration of Renewable Energy Sources to Improve Energy Security

Increasing energy capacity by using PHEVs/BEVs as MDS will allow for increased investment in renewable energies by alleviating concerns related to the temporarily highly variable nature of solar (daytime) and wind (primarily nighttime). Using renewable energy has benefits not only for the environment and air quality, but also for energy security by reducing reliance on the supply from oil producing countries.

This approach requires a policy shift to allow and encourage large scale use of the MDS for energy to support interfacing of renewable generation.

Reduce and Redistribute Pollution in the Electric Grid and Transportation Network

By shifting the source of pollution away from vehicles, PHEVs/BEVs will change the transportation-based air pollution problem from a mobile source issue to a point source issue. This redistribution of pollution will likely have the effect of reducing pollution because point sources are much easier to control and some already have emission caps in place. Hadley [25] conducted initial research into the potential air quality impacts of PHEVs/BEVs, describing the impacts of G2V charging on air quality, and considering the types of power generation that are typically used at different times of day (e.g., coal-fired generation is prevalent at night in some regions).

Some policies are already in place to ensure that the redistribution of pollution that will occur with widespread deployment of PHEVs/BEVs will actually lead to a reduction in pollution. Further policy analysis is needed to ensure that V2G and G2V services are incentivized to occur at times when it will result in the maximum improvement in air quality.

Create New Markets and Further Deregulate Existing Markets

PHEVs/BEVs are poised to open new markets and increase opportunities in existing ones. Carbon-trade markets should be aided because they facilitate the change of the transportation-based air pollution problem from a mobile source issue to a point source issue (as described earlier). While point sources of pollution are much easier to control, if they are nonrenewable, they will likely need to trade carbon credits to counter the increased emissions.

PHEVs/BEVs will also create new modes for participation in the electricity markets . There will be opportunities for businesses to act as Qualified Scheduling Entities (QSE) to the electric utility by facilitating V2G/G2V interactions. Such a QSE that aggregates across vehicles is necessary because any one vehicle's contribution will be too small to allow it to participate directly in the market. PHEVs/BEVs will likely function akin to small generators as a distributed energy resource.

Policy that enhances market development and deregulation allowing a new type of QSE to bid in a variety of markets is needed to facilitate the aggregated use of PHEVs/BEVs in "transportation-energy" markets.

Plan and Develop Energy Exchange Stations

Energy exchange stations (for G2V and V2G) could take one of at least two forms. The first, the way considered by most electric vehicle research to date, assumes that individual drivers plug in and charge their vehicle over a period of several hours. Some examples of potential charging station locations are shopping malls, recreational areas, schools, and of course homes.

Further, rather than requiring drivers to plug into the grid and wait several hours to charge their batteries, battery exchange locations could be as ubiquitous as gas stations and automatically exchange discharged batteries with fully charged batteries. Charging PHEVs in this way has benefits for drivers because the process takes only a few minutes as opposed to several hours. Also, this system would require a leasing system for batteries similar to the system in place for leasing cell phones, alleviating driver concerns about battery life. The benefit for utilities is that control over charging and servicing the grid is centralized.

In reality, charging (G2V) and discharging (V2G) services will likely be based on a hybrid of the two methods mentioned above (individual drivers plugging into the grid and stations designed to exchange batteries). Depending on the pricing structure in place, it may make sense for drivers to exchange batteries during long drives and plug in to a household plug at night. Incentive structures will need to be developed that consider the different players - energy exchange stations and individual drivers.

The temporal and spatial aspects of the activity patterns travelers choose (see, e.g., Fig. 1) adds a layer of complexity to the problem of locating charging stations to link the transportation and energy systems. This requires both micro (neighborhood, city, and metropolitan area) and macro (region, state, and nation) driver behavioral dynamics to be studied in detail. If appropriate incentives are developed, drivers could be encouraged not only to act in a way that best serves the grid, but also to act in a way that best serves the transportation system. The incentives could be passive such as pricing electricity for planned contribution at the location of charging facilities (either stations or induction charging embedded in the roadway), or active such as pricing electricity based on congestion in both the power grid and local transportation system. Cognitive and behavioral research is needed to determine the appropriate incentives.

Policy that addresses the planning requirements for charging stations and regulates emerging energy exchange markets is needed. Comprehensive policy that develops joint electricity and transportation programs for incentivizing drivers to participate in the transportation and electricity grid optimization are not yet proposed or even clearly defined.

Modeling of Complex Systems

To develop policy strategies that allow for faster and more significant penetration of PHEVs/BEVs, research is needed to model the interactive performance of two complex systems, power and transportation, linked through the behavior of individual vehicle operators, where this linkage is determined by the location of interface infrastructure. The behavior of travelers defines the required inputs into power modeling since time-dependent PHEVs/BEVs locations are critical. Every aspect of this meta-system enterprise (power, transport, consumer choice, and infrastructure development) is interlinked, therefore fully understanding policy issues is quite challenging. This section explores each aspect of the modeling approach beginning with transportation modeling, and then power systems modeling, then modeling the role of human agents, and finally determining economic feasibility (see Fig. 2 for illustration).

Transportation Modeling

Travel models typically contain demand and supply components. While most demand models used in practice are static and consider each leg of a trip separately, activity-based models are gaining momentum. Lemoine et al. [1] illustrate the problems that PHEVs/BEVs could pose if proper incentives are not given to ensure that energy exchange occurs at times beneficial to the grid. Activity-based travel models are better suited for PHEVs/BEVs modeling because they recognize that travel arises from a fundamental need to participate in activities, and thus the models capture trip-chaining behavior (e.g., home to work to grocery to home). Other benefits of activity-based models are the incorporation of intra-household interactions, interpersonal and intrapersonal consistency measures, consideration of space-time constraints on activities and travel, and emphasis on individual level travel patterns (as opposed to monitoring aggregate travel demands). A number of micro-simulation platforms that employ the activity-based paradigm of transportation demand forecasting have been developed in the last 5 years (e.g., [26-28]).

On the supply side, conventional techniques of trip assignment are static in nature, and consider vehicle flows aggregated over one or several hour time periods. The limitations of the static assignment procedures and the increase in computing capacity have allowed the field to move toward more behaviorally realistic dynamic traffic assignment (DTA) models . DTA techniques offer a number of advantages including capturing the spatial and temporal evolution of traffic dynamics across the transportation network, superior capability to capture traffic congestion buildup and dissipation, and explicitly representing the route-choice effect of external dynamic prices and other costs and incentives. A number of simulation-based DTA modules have been developed in recent years [29-32]. The above mentioned features of DTA make it an ideal choice for modeling the network congestion patterns induced by PHEVs/BEVs usage and their impact on other vehicles.

Travel models produce numerous outputs, metrics, and system properties. Of critical importance for connecting the transportation and energy models are predictions regarding time-dependent vehicle locations. This inference directly relates to the number of PHEVs/BEVs present at a specific power grid node, which will be related to the node's self-admittance described in the next subsection on power systems modeling. Consideration of multiple classes of travelers, PHEVs/BEVs and non-PHEVs/BEVs, will be critical until PHEVs/BEVs reach high percentage penetration.

It has been long understood that through pricing-based incentives, the system-level performance of transportation networks can be greatly improved. The entire field of congestion pricing (e.g., [33, 34]) addresses this fact. For instance, PHEVs/BEVs provide a novel opportunity to achieve gains in controlling and managing congestion in transportation systems through an incentive based approach that persuades users to act in an altruistic manner. Further, such incentives provide a unique opportunity (and complexity) in that dual objectives must be balanced: improving the efficiency of the transportation as well as that of the power system. For the transportation system, incentives influence route, departure, as well as destination choice. Incentives change the fundamental costs traveler's associate with their choices and a new general cost dynamic equilibrium emerges (for normal operating states). This requires a further broadening of the previously mentioned integrated modeling approach to include generalized costs as well as heterogeneous values of time.

Clearly, there will be significant uncertainty in the model inputs that must be built-in to ensure that the policy recommendations work well for a wide range of potential future outcomes. A vast amount of research has already been performed on stochastic transportation modeling both on the demand and supply side [35-40].

Power Systems Modeling

The planning, design, and operation of modern power systems call for extensive and detailed simulation. Models used to simulate power system behavior depend on the purpose and uses. When considering the need of studying PHEVs/BEVs impact on power system, different levels of modeling are required.

At the macro level, the power system planning related to the uses of PHEVs/BEVs requires understanding of the generation, storage, and load characteristics, as well as power flow projections impacted by the anticipated use of PHEVs/BEVs. A stochastic nature of PHEV/BEV use in the multiple possible roles will require advanced probabilistic methods for power flow analysis, as well as stochastic optimization related to operation and investment planning of dispersed generation [41, 42]. Enhanced modeling techniques must be developed for PHEV/BEV behavior as a load to assess dynamic stability of the power system operating in G2V mode [43]. Hadley [25] used the Oak Ridge Competitive Electricity Dispatch (ORCED) model to simulate PHEV/BEV electricity demand. It did not directly include transmission and distribution impacts, but discussed the issues of increased continuous transmission. Also, power system contingency analysis must be improved to account for the dynamic nature of both temporal and spatial properties of PHEVs/BEVs. In the V2G mode, PHEVs/BEVs may impact power grid operation in many different roles, both as energy storage used to improve performance of renewable energies such as wind and solar [44], as well as a market participant through aggregated distributed generation [10, 11, 45]. While it has been recognized that PHEVs/BEVs can be used for regulation services [10, 11], some studies also suggested the PHEVs/BEVs use for peak power "shaving" services [46]. A customized modeling tool that allows examining the potential impacts of large scale deployment of PHEVs/BEVs on a given electricity system, such as the "PHEV-load" tool developed by the National Renewable Energy Laboratory (NREL) may be needed [47].

At the micro level, the PHEV/BEV powertrain system itself, which is a very complex dynamic electromechanical system, may be studied. Specialized modeling and simulation tools, such as Argon National Laboratory's (ANL's) Powertrain System Analysis Toolkit (PSAT) are well suited for such an analysis [48]. This toolkit allows detailed modeling of charging and discharging dynamics of PHEVs/BEVs, which is crucial when defining properties of PHEVs/BEVs as loads, energy storage, or generation, as discussed above, Other ANL's tools such as GCtool, GREET, and AirCred may also be needed to asses other impacts [48].

The impact of PHEVs/BEVs ranges from the macro to micro scales, both in size and time. Different power system states (steady state, dynamic, and transient) may need to be represented in a framework using different types of mathematical formulations (waveforms, phasor, and algebraic). This leads to a new requirement for developing a method for linking different modeling techniques for accurate and efficient simulation when representing large scale penetration of PHEVs/BEVs as generators, storage elements, or loads [49].

Human Behavior Modeling

The widespread adoption of PHEVs/BEVs will place human vehicle operators at the intersection of power and transportation systems. Thus, it is critical to understand human decision making in the context of PHEV/BEV usage and how behavior can be shaped by incentive structures and training interventions. The large disparate group of decision makers includes not only drivers, but also utilities, battery exchange location coordinators, and fleet managers. Cognitive research will be critical to not only to understand and optimize human decision making involving PHEVs/BEVs, but to also increase the rate of PHEV/BEV adoption.

Route planning for any type of vehicle is an example of a dynamic decision task [50]. Choosing a route requires a series of interrelated decisions that occur in a changing and uncertain environment. PHEVs/BEVs introduce a number of additional decision elements, such as whether to draw energy from the grid or deliver energy to the grid at destinations with facilities allowing such interfaces. Complicating this decision process, G2V costs and V2G credits vary through time and are not perfectly predictable from the driver's perspective.

One successful framework for modeling human performance in dynamic decision making tasks is reinforcement learning (RL) [51, 52]. The theory of RL comprises an array of techniques for learning temporally extended tasks in dynamic environments. An agent is assumed to be immersed in its environment, with some number of actions available to be taken at any given time. The chosen action has an effect, depending on the current state of the environment, the immediate reward (or punishment) the agent receives, and the future state of the environment. Thus actions can influence situations and rewards arbitrarily far into the future, and successful performance hinges on effective planning and coordination of extended sequences of actions [53].

Previous research demonstrates that RL agents and humans are more likely to discover the underlying structure of a task when state cues are present that allow for generalization [54]. A state cue in the context of PHEV/BEV decision making would include observable properties - such as time of day, weather conditions, and congestion - that enable prediction of G2V credits and V2G costs. State cues play a critical role in shaping learning and it has been shown that variability in state predictors disrupts performance more than equivalent variability in the reward structure [55]. Further research is needed to examine how variability in state cues and reward structure affects PHEV/BEV route selection. Establishing how PHEV/BEV driver performance (with respect to improving conditions on the grid and transportation system) declines with variability in state cues is important because transient changes in incentives could have negative, unintended consequences, making it difficult for people to acquire the basic pricing contingencies. Research is also needed to find the best methods for PHEV/BEV operators or aggregators to learn about incentive structures. Various types of feedback are available (e.g., Reward Only, First Error), and the optimal approach should be determined via experiment.

Determining Economic Feasibility

To take advantage of the proposed "transportation-energy" markets , interface infrastructure - the facilities that will bridge the two systems and serve as energy transfer points - must be developed and planned. While prevalence of PHEVs/BEVs in the future is unknown, their ultimate value can only come if the interfaces are in place. This leads to a situation where the demand for PHEVs/BEVs depends on the infrastructure supply, which in turn is defined by the demand. The traditional project valuation models fall short of accounting for this feedback loop.

Developing interface infrastructure is a uniquely challenging problem because the equipment must not only adjust energy flow over time, but the location of transfer points must be determined to maximize long-term value and minimize risks. Technology adoption, incentives, and system interdependencies all play a role.

To maximize the value of developing interface infrastructure in a particular location, two aspects of the problem must be considered: (1) the value created to the grid by using PHEVs/BEVs for regulation services, and (2) the value of the activity-based travel patterns that could include a visit to the interface infrastructure. The former value can be explicitly determined, but unless the latter is considered and travelers are enticed to use the new infrastructure, the value to the grid will not be achieved. Typically, the traveling public selects route and activity patterns without considering energy exchange opportunities. New methodologies and modeling techniques must be developed for valuing interface infrastructure given its dependence on traveler behavior.

Unlike most past research into making investment decisions for infrastructure projects that focus on a single system (e.g., [56, 57]), the problem posed here must consider the interdependencies between several systems as well as the rate of technology adoption (availability of PHEVs/BEVs to use this facility and generate value). In fact, this problem exhibits both spatial network effects and strategic "bandwagon" network externalities (see seminal contributions in this area by Rohlfs [58], Farrell and Saloner [59], and David and Greenstein [60]).

It is clear that in the face of this bandwagon effect, the value of deferral flexibility is marginal. Hence, the project developer action space should consider actions that promote early adoption without fully committing to irreversible capital expenditures. Stochastic modeling approaches could be useful here to consider that the outcome and uncertainty space of the valuation problem is decision dependent (see, e.g., [61]).

Benefits

This section aims at demonstrating the potential benefits of PHEVs/BEVs that may be used to feed power back to home or office building, which is known as "Vehicle-to-Building" (V2B) operation . The new parking facility called "smart garage" is introduced and its eclectic power capacity is discussed. Based on the availability analysis of smart garages, a strategy to adopting PHEV/BEV uses in the V2B mode under peak load and outage condition is proposed. V2B approach considers PHEVs/BEVs as a generation resource for the buildings at certain periods of time via bidirectional power transfers, which could increase the flexibility of the electrical distribution system operation. It is expected that V2B operation will improve the reliability of the distribution system, provide extra economic benefits to the vehicle owners, and reduce the home or building electricity purchase cost based on the demand side management and outage management programs with customer incentives.

Demand Side Management (DSM)

For electric utility, DSM is defined as "Utility-sponsored programs to influence the time of use and amount of energy use by select customers," which includes peak clipping, valley filling, load shifting, strategic conservation, strategic load growth, and flexible load shape [62]. However, for utility end-user (customer), DSM is often understood to include two components: energy efficiency (EE) and demand response (DR). EE is designed to reduce electricity consumption during all hours of the year; DR is designed to change on-site demand for energy in intervals and associated timing of electric demand by transmitting changes in prices, load control signals, or other incentives to end users to reflect existing production and delivery costs [63]. By cooperative activities between the utility and its customers to utilize DSM, it will provide the benefits to the customer, utility, and society as a whole, which is summarized in Table 1 [64].

PHEVs and BEVs in Coupled Power and Transportation Systems. Table 1 DSM benefits to customer, utility, and society [64]

Customer benefits	Societal benefits	Utility benefits
Satisfy electricity demands	Reduce environmental impacts	Lower cost of service
Reduce/stabilize costs	Conserve resources	Improved operating efficiency
Improve value of service	Protect global environment	Flexibility of operation
Maintain/improve lifestyle	Maximize customer welfare	Reduced capital needs

In the V2B option, the owners will plug in their vehicles during the day at their final destination for a given time frame. As an example, this may be either at their workplace (central business district) or at the place of their study (university). The destinations, either parking lots or parking garages next to the buildings, are assumed to be equipped with a bidirectional charger and controller. The parking facility should allow either charge or discharge mode for the car batteries when necessary. The idea is that the parking facility can offer an aggregation service for charging the batteries when the building demand is lower than its peak load and discharge the batteries to partially supply the building to reduce the peak demand during a high demand. This mode will be considered as DSM by V2B. Considering the electricity rate when the vehicle batteries were charged is lower than when the batteries are discharged, the battery storage may be used to offset high cost during the peak demand.

Outage Management (OM)

Another important benefit of V2B is using the battery energy storage in PHEVs/BEVs as an emergency backup power for the commercial facility/building, which increases the reliability of the power supply for that load.

An outage is typically caused by several unplanned events, and a timely detection and mitigation of such situations is a real concern for the utility. Outage management system helps the operators to locate an outage, repair the damage, and restore the service. Outage management must be performed very quickly to reduce outage time. Recently completed project proposes an optimal fault location scheme which will help the operator to find the faulted section very quickly [65]. In this entry, the restoration strategy under an outage will be mainly discussed.

The following types of outages and studies about the impact of PHEVs/BEVs adoption are considered:

1. Outage beyond the distribution system: These may be caused by generator failure, fault in transmission line, or substation busbar. Usually spinning reserves are kept for these circumstances. From the previous studies it is concluded that PHEVs/BEVs can be a candidate solution for spinning reserves (as the traditional fastest acting spinning reserve generators are highly costly while PHEVs/BEVs qualify for fast response with lesser cost). One may consider using a real-time security constrained optimal power flow under the contingencies to calculate the amount of PHEV/BEV battery capacity required for a certain location at a specific instance.
2. Outage in distribution system: These may be caused by fault inside the distribution system and can be mitigated by precise spatial adjustment of PHEV/BEV battery generation that may be used to feed electricity locally during and after outage.

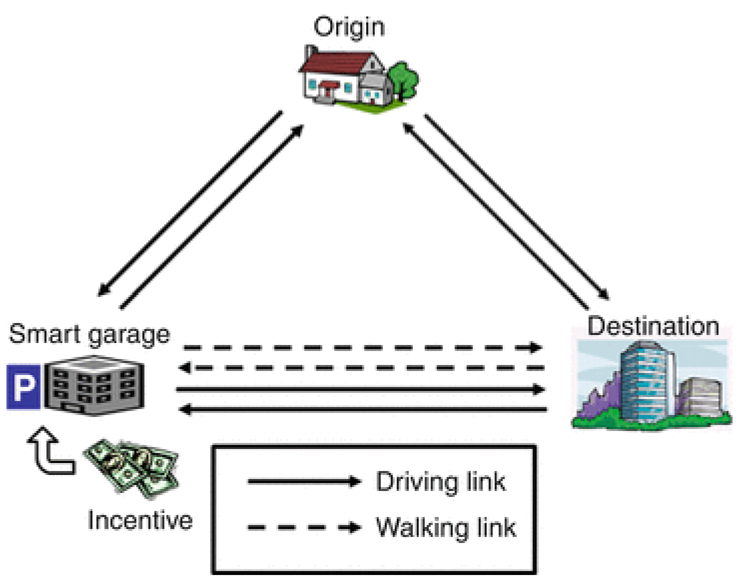
To propose the restoration strategy where PHEV/BEV batteries are used to mitigate an outage condition, the information about events (where the fault is located and how the impact will propagate) and the location of the battery storage need to be correlated. Thus, a spatial as well as temporal analysis should be performed.

The restoration strategy can be executed in the following steps:

1. Detect a fault.
2. Estimate the location of the fault.
3. Analyze the amount of battery generation required and the availability of PHEVs/BEVs that can provide an alternative generation support in the vicinity of the faulted area until the faulted section is repaired. This will also consider the generation duration requirement (i.e., time to repair the faulted section).
4. Schedule the aggregated PHEVs/BEVs generation optimally. This is a multi-objective optimization problem which can be formulated to minimize the distance between location of the fault and available PHEVs/BEVs battery generation locations as well as minimize the operating cost under system operation and security constraints.

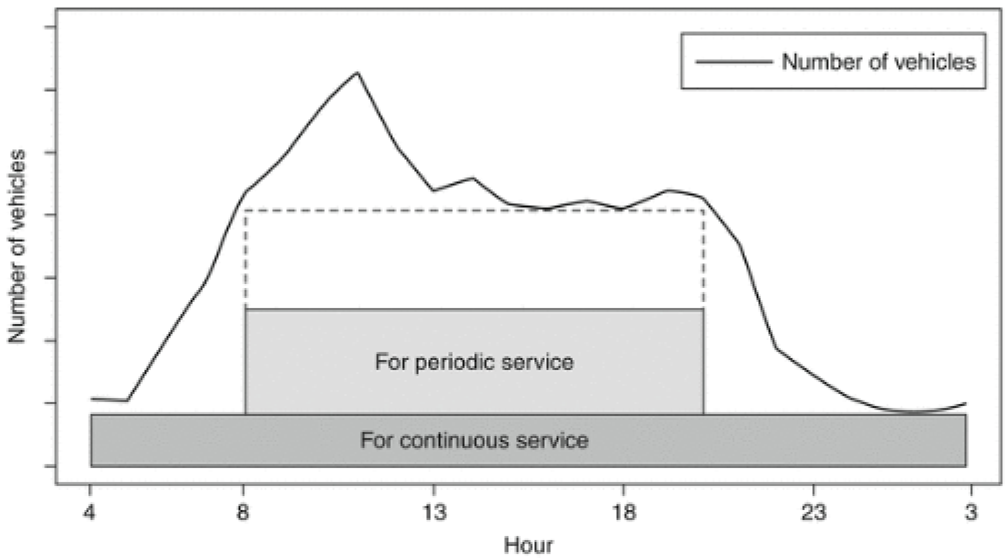
Garage Location and Charging/Discharging Infrastructure

Commercial and public parking garages in a central business district (CBD) provide thousands of parking spaces for commuters and visitors. After penetrating the conventional vehicle market, owners of PHEVs/BEVs will be using these parking garages , which may provide an aggregated service to act as an electric power source or storage.
Figure 6 shows a simple transportation network with smart garage building. As a smart garage is constructed, PHEV/BEV drivers have two options: proceed to final destination directly or park at the smart garage and walk to the destination along walking links. Drivers in transportation network select parking garage based on the location and financial incentives (less parking fee), which can be modeled as traffic assignment problem. Demand of smart garage (number of parked PHEVs/BEVs) calculated from the traffic assignment problem would vary by the location and incentive of the smart garage.



PHEVs and BEVs in Coupled Power and Transportation Systems. Figure 6 Simple transportation network with smart garage

Electric power capacity of smart garage is estimated based on demand of smart garage. Demand of smart garage building is not constant. Generally, the demand of smart garage building during the day would be higher than during the night, similar to the demand structure for a conventional garage as shown in Fig. 7. Due to the versatility, electric power capacity needs to be defined in two parts: for periodic service and for continuous service as in Fig. 7. The available electric power estimated based on the demand of smart garage can be used for determining the support service that can be provided during outage management and demand side management in vehicle-to-building (V2B) mode.



PHEVs and BEVs in Coupled Power and Transportation Systems. Figure 7 Demand of smart garage for a day

Case Study

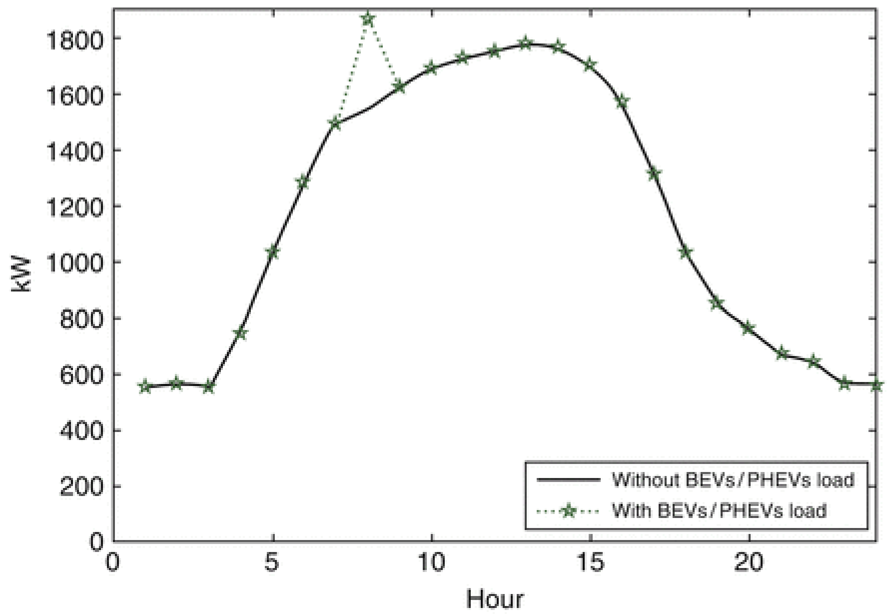
Test cases for two scenarios are studied: demand side management using V2B mode during peak power demand and outage management using V2B mode during faults.

Demand Side Management During Peak Power Demand

In this case, a large commercial building is analyzed to demonstrate the potential savings using demand side management based on V2B operation. Itron, Inc. prepared a technical survey for the California Energy Commission (CEC), which modeled difference commercial sectors, including large office building [66]. The load shapes include typical day, hot day, cold day, and weekend for each of four seasons. According to the definition used in this report, large office buildings are defined as premises with total floor area equal or larger than 30,000 sq ft. The largest electric end-uses in this building type are interior lighting, cooling, office equipment, and ventilation [66].
The summer typical load shape for a large office building is selected for our case study. The single building demand is obtained from the results reported in the literature [66]. The following assumptions are taken:

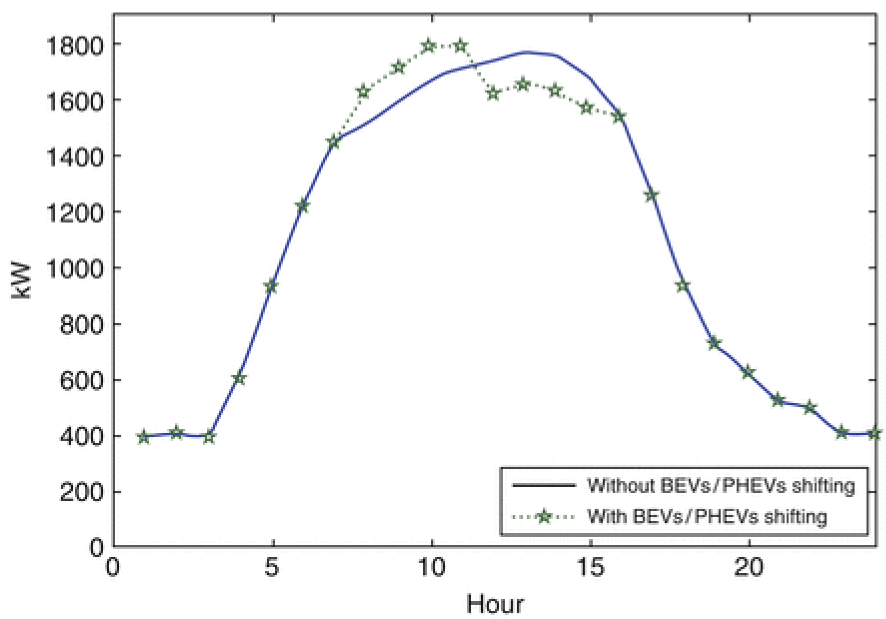
- The studied building is 450,000 sq ft.
- There are up to 80 PHEVs/BEVs that arrive at 8 a.m. and are available for the entire day.
- Maximum capacity of each vehicle is 10 kWh (very conservative for BEVs).
- The batteries in PHEVs/BEVs are drained by an average of 4.0 kWh by the driving cycle used.

When PHEVs/BEVs are on site, the building can charge the batteries during the morning hours (lower electricity price) and drain the batteries by an equal amount during afternoon hours (higher electricity price). Thus the owner of PHEV/BEV will have the required energy in his/her battery to make sure the driving cycle to return home can be met. Figure 8 shows the impacts of charging PHEVs by faster charging methods (AC Level 3 or DC charging). It will elevate the peak demand to 1.86 MW of the office building since the faster charging method will cause a large load in a short period (10-15 min), which is not recommend for either utilities or customers.



PHEVs and BEVs in Coupled Power and Transportation Systems. Figure 8 Impacts of faster charging PHEVs/BEVs on load demand

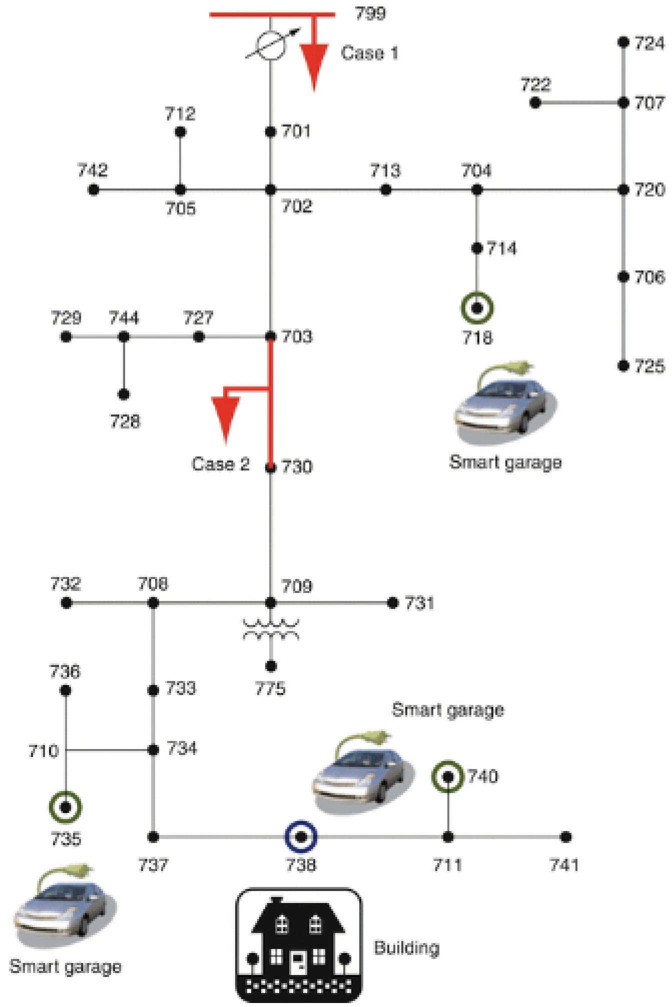
Figure 9 shows the change in the load shape for the typical summer day by using the AC Level 1 charging method defined by the Society for Automotive Engineers (SAE) J1772 [67]. The load curve was changed by shifting the afternoon peak load to the morning off-peak load when charging and discharging PHEVs/BEVs. Considering the rate structures for peak and off-peak load in commercial buildings, peak load shifting using V2B mode may provide the electricity bill saving. Further study could be conducted to show the total saving expressed in dollars.



PHEVs and BEVs in Coupled Power and Transportation Systems. Figure 9 Peak load shifting with PHEVs/BEVs for a typical summer daily load

Outage Management During Faults

The proposed restoration scheme was tested on a small distribution system (IEEE 37 node radial test feeder [68]).
This is an actual feeder located in California, which consists of several unbalanced spot loads. The nominal voltage is 4.8 kV.
Figure 10 shows the test feeder with smart garages at some nodes.



PHEVs and BEVs in Coupled Power and Transportation Systems. Fig. 10 Diagram of test feeder with smart garages

The following assumptions are taken:

- Three nodes are specified as smart garages (nodes 718, 735, and 740).
- Maximum capacity of each vehicle is 10 kWh.
- Discharge vehicles with state of charge (soc >70%.
- PHEV/BEV tariff for charging is 5 c/kWh and for discharging is (15-40) c/kWh (depending on different garages). Discharging tariff for node 718 is 40 c/kWh, for node 735 is 30 c/kWh, and for node 740 is 25 c/kWh.

Under normal operating condition, node no. 799 acts as an infinite bus and all the loads are fed through it. Two different outage cases are studied:

1. Case 1: Fault on or beyond node 799: PHEVs/BEVs at nodes 718, 735, and 740 were scheduled to satisfy all the loads on the feeder. Table 2 shows the case results.
2. Case 2: Fault on line segment 703-730: Node 799 will supply all the loads beyond this line segment. PHEVs/EBVs at nodes 735 and 740 will be scheduled to satisfy the island created by a fault on line 703-730. Table 3 shows the case results.

PHEVs and BEVs in Coupled Power and Transportation Systems. Table 2 Case study 1: results for PHEV/BEV generation scheduling

Node 718	Node 735	Node 740

Ph-1 (kW)	Ph-2 (kW)	Ph-3 (kW)	Ph-1 (kW)	Ph-2 (kW)	Ph-3 (kW)	Ph-1 (kW)	Ph-2 (kW)	Ph-3 (kW)
0	0	411	300	300	300	427	339	380

Total cost for three phases is $733.2/h

PHEVs and BEVs in Coupled Power and Transportation Systems. Table 3 Case study 2: results for PHEV/BEV generation scheduling

Node 735			Node 740		
Ph-1 (kW)	Ph-2 (kW)	Ph-3 (kW)	Ph-1 (kW)	Ph-2 (kW)	Ph-3 (kW)
300	127	300	51	0	81

Total cost for three phases is $221.35/h

Conclusions and Future Research

The policy implications of widespread PHEV/BEV deployment in the energy and transportation systems are explored. Previous research has approached the problem from selected angles, making many simplifying assumptions. Some thoughts on how the problem may be approached from a non-myopic perspective are provided.

In summary, numerous policy shifts are needed to realize the full potential of PHEVs/BEVs, and the cooperation of the transportation and energy sectors is vital. If policies such as the ones outlined in this paper are adopted, PHEVs/BEVs can provide many benefits to the electric grid in terms of reliability and stability by acting as mobile decentralized storage and allowing for vehicle-to-grid and grid-to-vehicle services. PHEVs/BEVs will also allow for enhanced penetration of renewable energy resources such as wind and solar, which will also aid with energy security by reducing dependence on foreign sources of oil. Important benefits can be made to air quality through transferring pollution from numerous mobile sources to fewer point sources that are easier to control and may participate in cap-and-trade markets. In addition to the carbon market, new markets will be created in power systems due to the potential for PHEVs/BEVs (or aggregators of PHEVs/BEVs) to participate, particularly with ancillary and regulation services. Lastly, charging stations must be planned and developed carefully to allow for flexibility in driver options and optimal performance of the transportation and electricity networks.

The proposed multi-layered modeling framework considers the spatial and temporal nature of the system interactions. PHEV/BEV time-dependent travel patterns are outputs of a transportation model and inputs to power systems model . The framework also includes cognitive behavior modeling for the purposes of developing appropriate incentives to encourage drivers to behave in a way that improves the efficiency of the transportation and energy systems.

The potential benefits of using PHEVs/BEVs as dynamically configurable dispersed energy storage that can serve as load or generation in a power system as needed is discussed. If serving in G2V as well as V2B mode and if aggregated, PHEVs/BEVs may play a major role in both the electricity and the transportation networks. Selecting garage location and charging/discharging infrastructure needs special attention from the transportation system demand point of view. For demand side management in electricity networks, the use of PHEVs/BEVs to create a peak load shifting strategy can reduce the electricity purchase cost for the customer and vehicle owner. For outage management in electricity networks , the use of PHEVs/BEVs to generate power during outage restoration stage is envisioned by solving a multi-objective optimization problem of merit-order scheduling of PHEVs/BEVs under operating constraints.

In recent years, Smart Grid revolution has begun with the sponsorship and involvement from government, businesses, utilities, and other stakeholders, especially with the development and integration of renewable energy resources. Envisioning the longer-term impact, if there is enough aggregated PHEV/BEV vehicles, such as a fleet, they can serve as backup generation and storage for renewable energy in smart grid applications. Many other functions of the future electricity network may be affected when PHEVs/BEVs act as dynamically configurable energy storage, which may have profound impact on the transportation networks as well. Better understanding of the role of PHEVs/BEVs in coupled power and transportation systems will be beneficial to transform existing power grid into the Smart Grid, a power system that is more efficient, reliable, resilient, and responsive.

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PHEVs and BEVs in Coupled Power and Transportation Systems

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