Energy Management Framework for Mobile Vehicular Electric Storage

Nan Chen, Jinghuan Ma, Mushu Li, Miao Wang, and Xuemin (Sherman) Shen

ABSTRACT

Worldwide legislative, industrial, and technical progress is propelling PEV to dominate the future automobile market. While large-scale simultaneous charging of PEVs can place great pressure on the existing power infrastructure, the PEV, foreseeing the potential in energy delivery with its mobile and energy-storing features, can be utilized to flexibly mitigate grid overload issues. In this article, we discuss the energy management issue in a scenario with strong intersection between transportation and power systems due to enormous PEV deployment. To realize the energy-storing potentials of PEVs, they are used as energy storages to deliver energy among charging stations, referred to as MVESs. By conveying MVES roles in the transportation system, we introduce a joint model of power and transportation systems to quantify the MVES impacts on the on-road traffic. Then, an energy management framework is proposed to mitigate the overload issues with MVESs while guaranteeing time-efficient energy delivery in the transportation system. Modelling and optimization methods are introduced in detail. A case study is conducted to validate the effectiveness of the proposed framework. Finally, we discuss open research issues that can optimize future MVES energy management.

INTRODUCTION

The environmental concern of heavy fossil fuel usage motivates the development of plug-in electric vehicles (PEVs) to reduce carbon dioxide emission. Policy-wise, legislation has been launched globally to ban petrol-powered vehicles. In 2016, Germany passed a resolution to realize all emission-free cars for on-road use by 2030 [1]. Motivated by government legislation, PEV commercialization is proceeding rapidly as conventional car producers all have their grand plans of PEV manufactures. For instance, BMW plans to have all its models electrified by 2021. As lithium-ion battery technology develops, the battery cost is expected to decrease to as low as \$73/kWh by 2030 [2], making PEVs cost competitive with conventional petroleum-based vehicles. Meanwhile, the development of solid-state lithium battery technology could contribute to a safer, lighter and more energy-efficient PEV in the future [3].

Owing to political, industrial, and technical supports, PEV will inevitably dominate the automobile market. As predicted by [4], by 2030 there will be 56 million PEVs in the automobile market, while the battery capacity increases to 120kWh on average. Considering the predicted PEV amount and the battery capacity, the charging demands (also energy storage potentials) can reach up to 6.7GWh, bringing both advancements and challenges to the power system.

On one hand, the large penetration rate of mobile PEVs introduces stochastic power demand to the power system, posing non-negligible impacts on the system operation [5, 6], for example, voltage and phase imbalance and so on. On the other hand, the considerable battery capacity of PEV provides a flexible solution to mitigate overload issues as on-road energy storages. Therefore, efficient energy management of PEVs (i.e., charging and discharging) is essential for the future power system.

To satisfy the increasing PEV charging demands at different energy levels, charging stations (CSs) are deployed in the power distribution system with different loading levels. Public CSs are usually deployed at distribution feeders with a high voltage (4-35kV) and loading (up to 4MW) capacity. Some of the CSs with high loading capacities and sufficient power supply in urban areas are referred to as resourceful CSs (RCSs). Other CSs in rural areas that have relatively limited loading capacities are referred to as limited capacity CSs (LCSs). Time-variant PEV traffic can lead to extensive PEV charging demands at the LCSs, overloading the feeders at peak hours.

To mitigate the potential overload issues, several solutions have been proposed in the literature [6, 7]. One intuitive method is to deploy stationary energy storage devices (e.g., batteries) at LCSs to satisfy the surplus charging demand. However, the installation of batteries not only increases the capital expenditure on the infrastructure, but also leads to inevitable energy redundancy during daytime hours. Moreover, as the traffic regimes evolve over years, the PEV charging demands can also change spatially, whereas the stationary storages do not have the flexibility to address the spatial variation.

With the similar energy-storing principle, PEVs can be seen as mobile batteries that move on-road to deliver surplus energy from RCSs to adjacent LCSs. The predicted PEV domination in the automobile market means that there is no excess expenditure on battery installation. Moreover, the large fleet size of mobile PEVs provides the power system with a spatially flexible energy storage choice that is well suitable to the variant PEV charging distribution incurred by traffic

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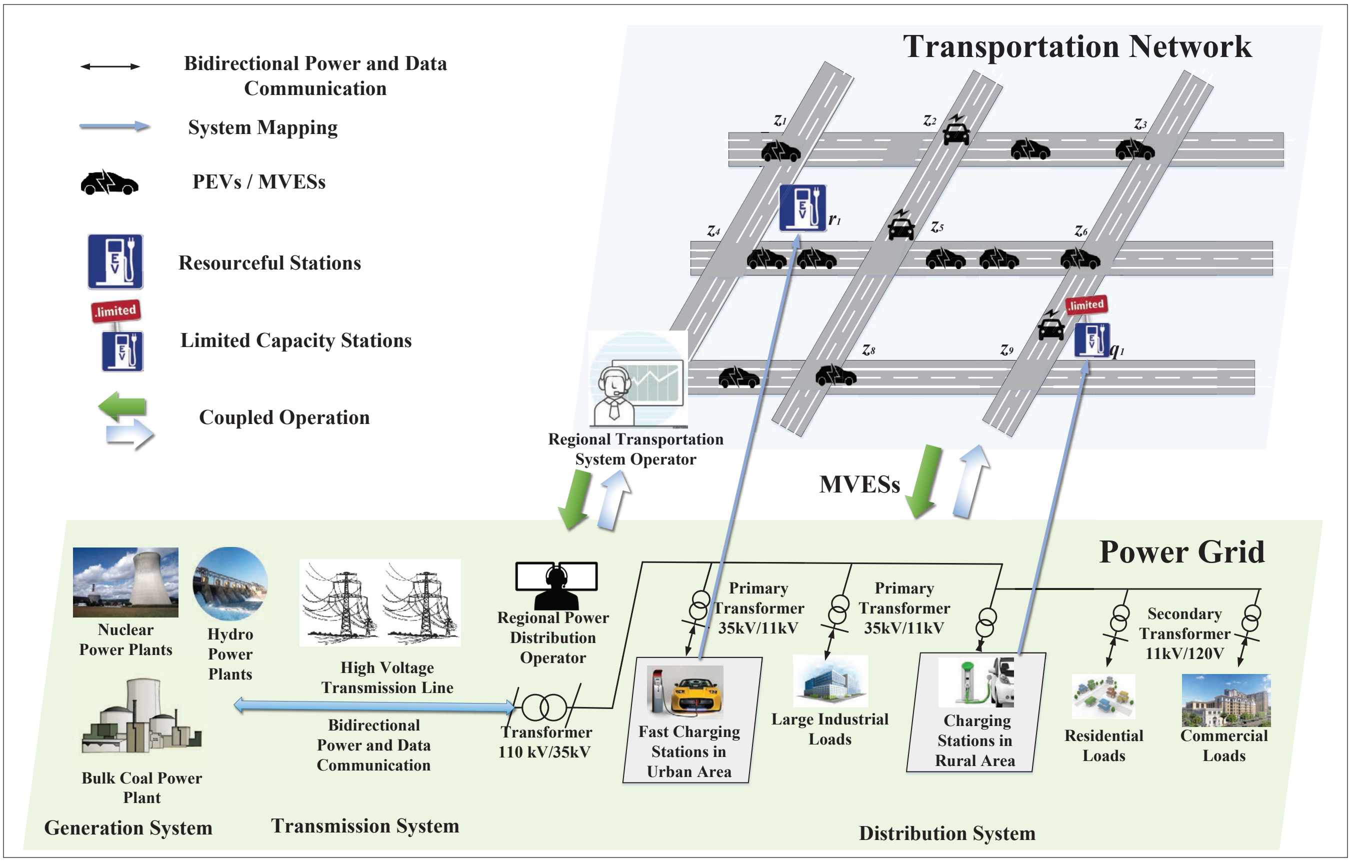

FIGURE 1. Joint model of power and transportation systems.

regime evolution. Therefore, in this article, we propose to utilize on-road PEVs as energy porters to deliver energy among a group of CSs (GCS) with time-variant charging distribution. We refer to these PEVs as mobile vehicular electric storages (MVESs).

In addition to the advantages, the introduction of MVESs also brings challenges to the system operation. The mobility of the MVES not only brings storage flexibility, but also adds fluctuation to the on-road energy delivery capacity. Some existing works model the PEV velocity transition and charging process as a Markov Chain to study the CS operation dynamics [7, 8]. Moreover, as part of the transportation system, MVESs couple the operation of power and transportation systems when a large MVES fleet participates in the energy delivery tasks. The work in [9] models the power and transportation systems as an extended transportation graph to study the coupled operation. However, the potential of PEVs as MVESs remains an open research issue. As the MVES energy delivery process consists of charging at RCS, on-road travelling, and discharging at LCS, the management of MVESs requires thorough system modelling and management.

In this article, we first introduce the power and transportation systems and a joint graph model that illustrates the interaction between systems. Based on the joint model, an energy management framework is proposed to achieve time-efficient energy distribution among a group of CS (GCS). Modelling and optimization methods are then introduced, and a case study is conducted to validate the effectiveness of the proposed framework. Open research issues are also discussed to further optimize the energy management of MVESs.

The remainder of this article is organized as follows. The joint model of power and transportation systems is introduced in the following section. The energy management framework is then proposed. Methods for an MVES energy management framework are introduced, followed by a case study. Then, open research issues are discussed. Finally, conclusions are given.

Joint Model of Power and Transportation Systems

When MVESs are incorporated into the power system for energy delivery, the increasing PEV charging demands could lead to an increasing number of MVESs injected into the transportation system. In the case of a dense traffic condition, the additional MVES traffic could incur non-negligible travelling delay or even traffic congestion on-road. The possible delay can reduce the time-efficiency of MVES energy delivery service, further resulting in GCS energy imbalance. Thus, the operation of power and transportation systems is coupled, as shown in Fig. 1. In this section, we discuss the environment of MVES management from both the power and transportation system perspectives.

Power System Sector

Power System Structure: The power system consists of a regional power distribution operator (RPDO), generation system, transmission system, and distribution system, as shown in the lower

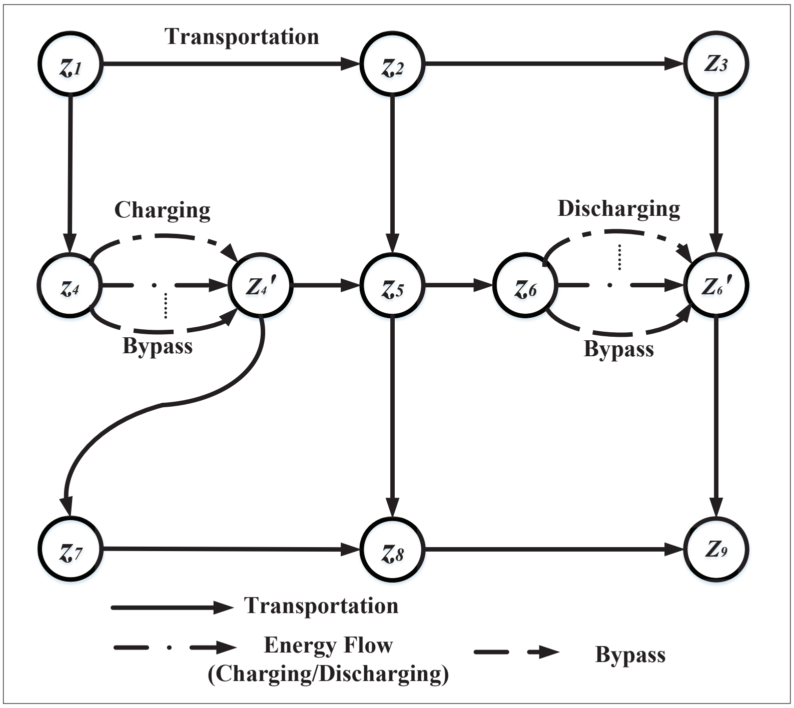

FIGURE 2. Graph model of the joint system.

part of Fig. 1. The RPDO is responsible for the local region power distribution. The RPDO aims to achieve power balance under the power system constraints. As the communication technology develops, the RPDO can effectively communicate with GCS and MVESs. The generated electricity from the generation system is transmitted through the transmission system to the distribution system where RCSs and LCSs are deployed.

RCSs: RCSs are normally deployed at large-capacity feeders (e.g., up to 4MW) that can sufficiently supply incoming PEVs for charging demand at peak hours. To satisfy high charging demand, RCSs are usually equipped with a sufficient number of fast chargers. In addition to supplying PEV charging at peak hours, RCSs have redundant charging availabilities during off-peak hours. Thus, they can be great candidates as power suppliers for LCSs.

LCSs: CSs with relatively small feeder capacities are normally deployed remotely from the energy-dense areas where the supply is limited and expensive, regarded as LCSs. LCSs are usually equipped with lower power chargers. As PEV commercialization proceeds, LCSs encounter an increasing charging demand, which could lead to potential overload. To mitigate the overload issue without excessive upgrade expenditure, MVESs are discharged at LCSs to provide additional energy.

To efficiently utilize the local energy, adjacent RCSs and LCSs are clustered together as a GCS using MVESs to deliver energy. From a long-term perspective, as the traffic regime evolves, the PEV charging demand distribution varies. Thus, the roles of RCSs and LCSs are also evolving due to the distribution variation. As a mobile and flexible energy storage, MVESs can effectively achieve power balance among GCS even facing the traffic evolution.

MVESs in the Power System: The MVES energy delivery process consists of three steps: charging at RCS, on-road traveling, and discharging at LCS. The energy efficiency of MVES charging and discharging can be as high as 95 percent when the DC-DC converters of CS chargers perform optimally. Meanwhile, the energy efficiency of MVES travelling on-road is over 99 percent since the energy retention loss of an MVES battery during travelling is negligible. Thus, the MVES energy delivery service has a high energy efficiency around 90 percent [10]. In terms of their battery size and ownership, MVESs are categorized into three types: utility-owned MVESs (UMVESs), legislation-motivated MVESs (LMVESs) and private MVESs (PMVESs).

UMVESs: Inspired by the oil tanker, the RPDO uses huge battery capacity PEVs to deliver energy to LCSs. These huge battery capacity vehicles are referred to as UMVESs that are frequently charged and discharged on demand;

LMVESs: As the legislation launched by the government encourages PEV purchase/lease, vehicle fleet-based companies (e.g., vehicular rental and taxi companies) are potential candidates for purchasing PEVs as LMVESs. LMVESs are small battery capacity MVESs with a large fleet size that fulfill the company's assigned tasks;

PMVESs: As the PEVs gradually dominate the automobile market, private PEVs can be stimulated as PMVESs to transmit energy for additional economic benefits. Similar to LMVESs, PMVESs transmit a small amount of energy with a large fleet size. PMVESs make independent energy delivery decisions to maximize their service reward.

TRANSPORTATION SYSTEM SECTOR

The transportation system is shown in the upper part of Fig. 1. CSs are deployed at traffic intersections (e.g., z_i) for easy access. To evaluate the traffic condition, we use the link between intersections (e.g., $L_{(i,\ j)}$) as the basic transportation modelling unit. When modelling the transportation system, traffic flow, density, and speed are the main parameters that can help calculate the travelling time along each link [11].

The regional transportation system operator (RTSO) aims to manage the traffic within their control area by optimizing the transportation cost (e.g., delay, etc.) under system constraints. The introduction of MVESs can interfere with the regular transportation operation, which is discussed as follows in terms of their types and fleet sizes.

UMVES: When only UMVESs are used to deliver energy, their impacts on the on-road traffic are negligible as only a limited number of UMVESs will be on the road for the service.

LMVES and PMVES: When LMVESs and PMVESs are travelling on-road, they themselves account for a considerable proportion of the on-road traffic that has non-negligible impact on the traffic condition. If the demanding energy of LCSs requires 100 MVESs for the service and all MVESs travel along an already busy road, severe congestion could incur. Therefore, the utilization of LMVESs/PMVESs makes MVES energy management an interdisciplinary research area, requiring a joint modelling of power and transportation systems.

Joint Graph Model for MVESs: A directed graph model is used to jointly characterize both the power and transportation operation. As shown

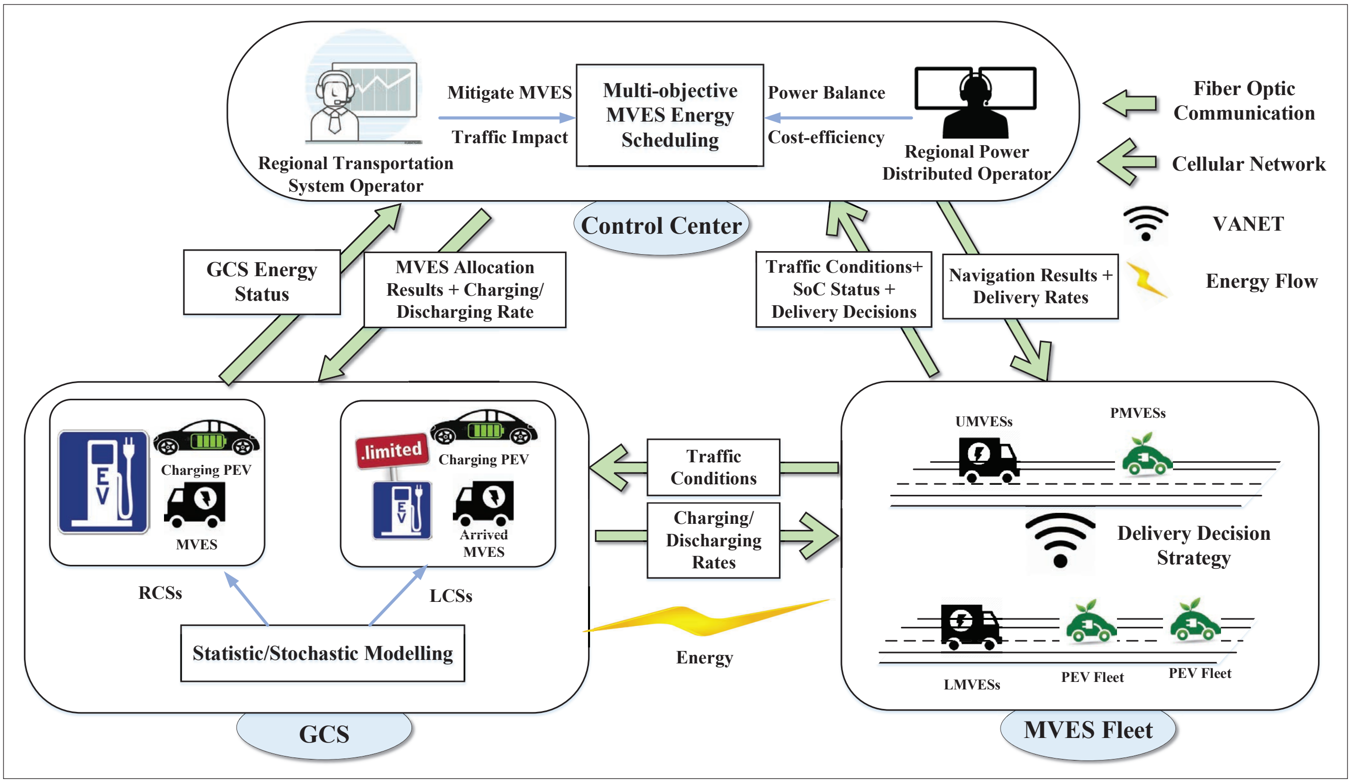

FIGURE 3. Energy management frameworks for MVESs.

in Fig. 2, the road intersections are represented by vertexes and links are represented by solid-line edges. Operation processes in-stations are added in the graph as virtual edges in dash-line. Next, we introduce each component of the graph.

Transportation Link: According to [12], as the traffic density increases, the traffic gradually saturates, resulting in road congestion. To enable uncongested traffic, the traffic density and traffic flow are expected to be within the link capacity range which can be obtained based on the link lane number and historic traffic data. Meanwhile, the edge weight is characterized as the travel time of the road link;

RCS Dynamics: When MVESs arrive at RCS (e.g., vertex z_4), they need to decide whether to charge at this station, or bypass it. If MVESs choose to charge at the RCS, in terms of MVES energy storage capacities, they enter charging links with different edge weights. The edge weight denotes MVES charging time, depending on the MVES energy storage and RCS charging power. If the station is not MVESs' ideal charging spot, they can choose to charge at other stations, and enter the bypass link with zero time cost;

LCS Dynamics: Discharging spots are reserved for MVESs in LCS. If MVESs decide to discharge at a LCS, they enter the discharging edge in dash line. The weight of discharging edge is represented by the discharging time. Depending on the CS adopted power standard, the weight also varies. When MVESs do not supply energy at the arrived LCS, they will go through the bypass link with zero time cost.

The joint graph provides a comprehensive view of the MVES energy delivery process by scaling both power and transportation systems. With the introduced graph and proper MVES modeling, we can obtain the MVES energy status and delivery time, which will be the input data in our proposed framework.

ENERGY MANAGEMENT FRAMEWORK FOR MVESS

As the PEVs gradually dominate the automobile market, the spatial and temporal variations of MVES energy capacity vary accordingly. Moreover, the operation processes of GCS also demand management to enable the time-efficiency of MVES energy delivery. Thus, we propose a comprehensive energy management framework to achieve time-efficient energy delivery among GCS, as shown in Fig. 3. First, the main management entities are introduced. Then, a heterogeneous communication network is introduced for efficient information exchange.

CONTROL CENTER

To enable both power and transportation systems operating smoothly, the RPDO and RTSO collaborate together to schedule MVESs among GCS. Thus, a multi-objective optimization problem that has both transportation and power objectives/variables is formulated at the control center. For the RPDO, the MVES energy delivery service helps the local distribution system achieve power balance in a timely manner. To schedule different types of MVESs, the RPDO either orders direct commands to schedule obedient MVESs or stimulates the fleets with price signals.

For the RTSO, when a large number of MVESs are introduced in the transportation system, they could have a non-negligible impact on the traffic condition, delaying both MVESs and other on-road vehicles. Thus, the RTSO schedules the on-road MVES traffic to enable the time-efficiency of the transportation operation. Depending on

Some PMVESs would prefer a shorter service time while others may tend to minimize battery degradation costs. Based on the received reward and task information, PMVESs make their service decisions, which are then transmitted to the control center to confirm the energy delivery tasks.

the local traffic and GCS energy status, the optimization problem adjusts the weights of different optimization objectives to achieve the optimal scheduling result.

During each scheduling period, the control center first receives the energy status from GCS, traffic condition and State-of-Charge (SoC) statuses of on-road MVESs. Then, based on the received data, the control center optimizes the scheduling cost under both power and transportation constraints, and provides the MVES allocation results to GCS, along with price signals (e.g., charging/discharging rates, and so on). The control center also sends the energy delivery tasks and navigation directions to MVESs.

GCS

GCS is defined as a CS cluster of adjacent RCSs and LCSs in a geographically approachable coverage (e.g., 30km) by MVESs. During each scheduling period, each CS in the GCS estimates its surplus/demanding energy using statistic and stochastic modelling (which we will discuss later), and sends the result to the control center. After the MVES energy delivery service is scheduled at the control center, the MVES allocation results will then be sent back to GCS so that they can prepare for MVES charging/discharging (e.g., reserve MVES service spots).

MVES Fleet

As required by the RTSO, MVES fleets constantly transmit the on-road traffic conditions to the control center for traffic update and prediction. MVES SoC statuses are also sent to the control center so that the on-road MVES service capacities and their travelling ranges can be obtained by the RPDO. When the control center finishes the MVES scheduling, different signals are sent back to MVESs in terms of the MVES types. Belonging to the power utility company, UMVESs fully follow the received travel navigation and fulfill the energy delivery tasks. Meanwhile, for LMVES fleets, the assigned tasks will be fulfilled when the fleet achieves sufficient profits or has a settled-down contract with the power utility company to provide energy delivery service. For PMVESs, they receive additional rewards (e.g., economic benefits, charging priority, and so on) for energy delivery motivation. Each PMVES aims to maximize its individual energy delivery service revenue, which depends on the driver's preference. For instance, some PMVESs would prefer a shorter service time while others may tend to minimize battery degradation costs. Based on the received reward and task information, PMVESs make their service decisions (e.g., accept, reject), which are then transmitted to the control center to confirm the energy delivery tasks.

Heterogeneous Communication Network

While the control center needs long-distance stable data exchange with GCS within a wide geographic area, the communication coverage of MVESs requires mobility-enabled communication. To achieve stable and efficient communication, a variety of technologies are required for data exchange between different entities, forming a heterogeneous communication network [8, 13].

The massive data exchange occurs in wide area networks (WANs) and neighborhood area networks (NANs). The control center constantly exchanges traffic and command information with GCS to enable regular management updates. As the transmitted data are closely related to the power system operation, a highly secured and stable communication technology such as fiber optic is required.

For MVESs, when they communicate with GCS and the control center on-road, the communication technology not only needs to support mobile and timely data transfer, but also covers a wide area considering vehicular mobility. In addition to adopting cellular networks for mobile data communication, emerging technologies such as space-air-ground networks can be adopted to enable data coverage in the rural areas with a satellite network while offloading the communication tasks in data-dense areas with an aerial network. When MVESs communicate with other MVESs on-road, the data communication range is shorter but the mobility requirement is higher. Emerging technology such as vehicle ad-hoc networks (VANETs) can be a good candidate. By deploying road side units (RSUs) along the road and on-board communication facilities on MVESs, vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications can be conducted on the move.

Methods for MVES Energy Management

MVES energy delivery scheduling is a complicated problem which not only requires the modelling of both on-road vehicular mobility and CS operation dynamics, but also demands optimization tools to solve the formulated problem. To enable effective MVES energy delivery among GCS, in this section, we introduce modelling/optimization methods for MVES energy management.

Markov Chain

Markov Chain is a stochastic model that describes a series of possible events that satisfy the Markov property: the probability of the event only depends on the present status (memoryless). It is a commonly used mathematical tool that can effectively model the queueing system, which CS are modelled as.

Considering the in-station chargers as servers, and incoming PEVs and MVESs as costumers/energy providers, the CS operation dynamics can be modelled as a multi-server queueing system [7]. Each state in the Markov Chain can denote a different charger-occupied state. Then, in terms of the vehicle arrival rate and service rate (i.e., charging/discharging rate), the probability of each state can be calculated to estimate the CS operation condition.

Wardrop's Principle

Considering that each driver is identical, non-cooperative and rational, drivers will choose their presumably shortest route. Thus, the transportation system will be at Wardrop's equilibrium (first principle) [9], such that no driver can reduce their travel time by unilaterally choosing another route of the same origin-destination pair. The equilibrium can also be applied in the case of joint power and transportation system operation. In this case, the traffic model becomes a power-traffic model with CS dynamics characterized as the travelling time as in Fig. 2. The method is very suitable for scheduling PMVESs by modelling them as individual travellers that aims to reach their Wardrop Equilibriums. On the other hand, the control center can also change toll fees on the road to achieve the optimal traffic results, known as the Wardrop's second principle [9].

CONVEX OPTIMIZATION

Convex optimization is widely applied in the engineering area to minimize a convex function over a convex set. With some commonly used methods (e.g., Karush-Kuhn-Tucker (KKT) conditions, Lagrangian multipliers and so on), the global optimized result can be obtained. While some PEV management problems can be easily formulated as convex optimization problems, other complicated problems can be non-convex. For example, when optimal power flow analysis is used by the RPDO to minimize the overall generation cost under the power constraints, the problem is non-convex due to the line current constraint [11]. In this case, linearization techniques and alternate minimization techniques are employed to obtain exact or sub-optimal solutions.

GAME THEORY

Compared with a centralized optimization problem, game theory provides a more realistic model to study the interaction among individual entities. Depending on the interaction among control center, GCS, and MVESs, different game models can be adopted.

Stackelberg Game: Stackelberg Game is a non-cooperative game with two types of players: the leaders who make decisions first and the followers who make their decisions in response to the leaders' decisions. When the control center acts like the leader to make scheduling decisions and MVESs are the followers to make their energy delivery decisions accordingly, the Stackelberg equilibrium can be obtained.

Coalitional Game: While MVESs are normally considered as competitors toward each other, they can also cooperate with each other to obtain an overall beneficial result, as in the coalitional game. This model can be very realistic and effective for LMVESs considering that the MVES fleet could belong to the same company that intends for a more beneficial result overall.

CASE STUDY

In this section, a case study is conducted to show the framework's effectiveness from two perspectives: overload mitigation and energy delivery time-efficiency.

We consider a GCS deployment in the Los Angeles (L.A.) area, as shown in Fig. 4, where RCSs are deployed in L.A. Downtown and Boyle Heights while LCSs are deployed in Santa Fe Springs and Norwalk. RCSs (r_1 and r_2) have sufficient loading capacities of 2.4MWh and 1.8MWh, respectively, adopting the SAE CCS level 2 charging standard with a charging power of 90kW. LCSs (q_1 and q_2) have limited loading capacities of 420kWh and 360kWh, respectively, with a charging power of 60kW. Different traffic links connect CSs within the area: MVESs can travel from r_1 to r_2 through the traffic links of I-110S-I-101S or I-10E. From r_2 to q_2, MVESs can travel by either the traffic links of I-5S-I-605S or I-5S-I-710S-I-105E. All traffic flow data are obtained from the California department of transportation PeSM, and the link capacities are estimated based on PeSM data [12, 14].

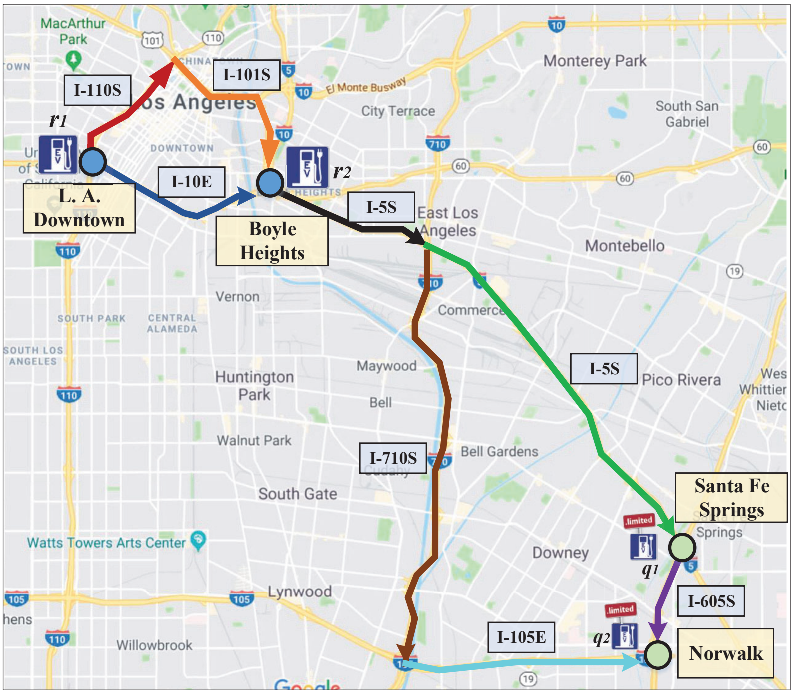

FIGURE 4. GCS deployment at Los Angeles area.

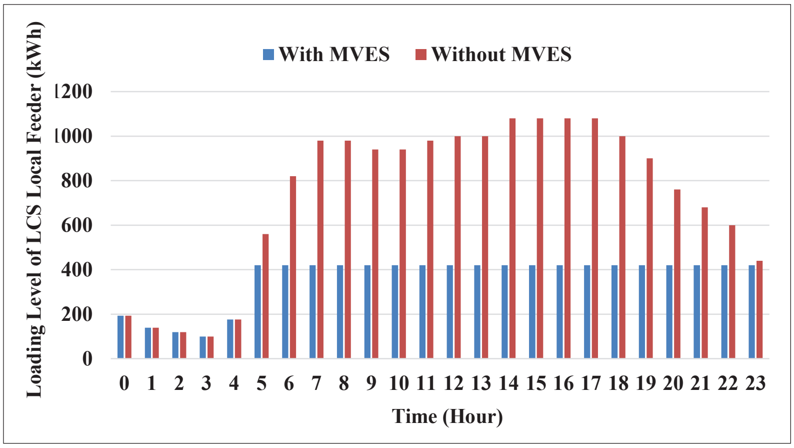

FIGURE 5. Overload Mitigation Performance at LCS.

We consider a PEV penetration rate of 15 percent. Analyzed by [4], 30 percent of on-road PEVs will be in the SoC range of 15 percent-50 percent, demanding charging. Among these PEVs, 20 percent of them arrive at CSs for charging. An average PEV charging energy of 20kWh is considered. Meanwhile, each MVES has an average energy storage capacity of 10kWh. Each LCS has a blocking probability of 10 percent, which means 90 percent of incoming PEVs can be charged immediately when they arrive at the CS.

From the power system perspective, the overload mitigation performance of LCS is shown in

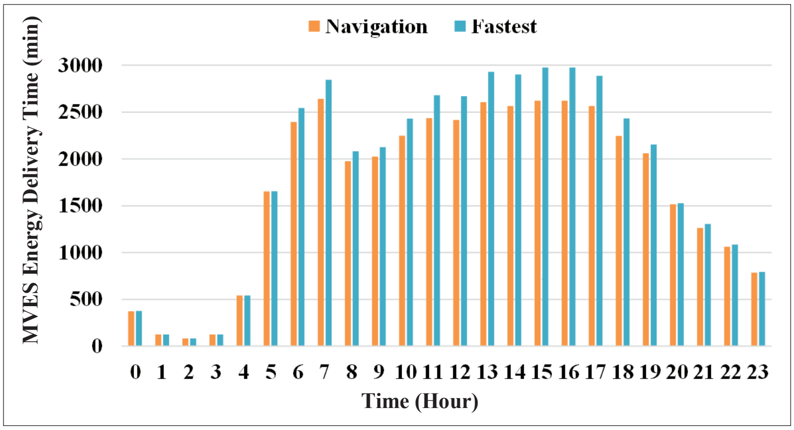

FIGURE 6. Service time-efficiency performance.

Fig. 5. Comparing the loading level of LCS local feeder in two scenarios, without and with MVES energy delivery, it can be seen that from 12 a.m. to 4 a.m., the loading of the local feeder with/without MVESs are the same, as the charging loads are within the station's feeder capacity, hence, no MVESs are required. However, starting in the morning, without MVES energy delivery, the charging load increases and constantly stays around the peak value, as the on-road traffic gradually increases. During the same time periods, with MVES energy delivery, the overloaded part is supplied by MVES delivered energy as managed by the framework, presenting an effective overload mitigation result.

We compare the service time efficiency performance of the proposed MVES management scheme with the fastest route scheme, as shown in Fig. 6. In the fastest route scheme, MVES drivers choose the fastest route without consider the additional MVES impact on the transportation system. It can be seen that from 11 p.m. to 4 a.m., the proposed management scheme and fastest route scheme have almost the same energy delivery time since there are a few MVESs on-road for energy delivery service. Starting in the early morning, the fastest route case has a longer delivery time, which hits the peak value in the afternoon. As the traffic flow increases during the daytime and becomes more dense in the afternoon, the increasing MVESs on-road can worsen the traffic condition without proper management (as in the fastest route scheme). Meanwhile, the proposed scheme in this scenario guides MVESs choosing other routes with lower traffic intensity, making the energy delivery time-efficient.

OPEN ISSUES

To fully utilize the on-road resource, the energy storage potential of PEVs as MVESs need to be thoroughly studied in the interdisciplinary area of power, transportation, and communication systems. In this section, we discuss open research issues that facilitate efficient MVES energy delivery among GCS.

MVES Incentive Mechanism: As the PEV market gradually matures, an increasing number of PMVESs are expected to participate in the energy delivery task. To be frequently charged/discharged as MVESs, concerns such as battery degradation arise. To motivate PMVESs, the control center provides incentive mechanisms such as dynamic pricing, charging priority rewards, and additional battery warranty.

Battery Management: One of the most concerned issues of the PEV battery is its life cycle. UMVESs need to enable a long life cycle to prolong their service time for the power system, and LMVESs/PMVESs also want to minimize battery degradation cost with frequent charging/discharging. Consequently, the control center can consider the battery degradation cost as one of the MVES scheduling factors to evaluate their task availability.

Spatial Extension of GCS: As PEV commercialization proceeds, to satisfy the increasing PEV charging demands, extensive CSs are deployed in the distribution system. As the spatial coverage of GCS extends, CSs in a GCS could belong to different power utility companies, thus becoming competitors to each other. As both CSs and MVESs operate competitively, a hierarchical game framework is required.

Security and Privacy of Data Communication: As a heterogeneous communication network is adopted in the proposed framework, security and privacy issues arise. Within the control center, the inter-system data exchange between the RPDO and RTSO could incur privacy issues. To enable a secured data exchange, fully homomorphic encryption such as summation can be used [15]. Meanwhile, as the communicated data among the control center, GCS and MVESs include system operation status and MVES battery information, the data integrity needs to be guaranteed and access control should be protected from malicious attack.

CONCLUSION

In this article, we have proposed to use PEVs as energy storages to deliver energy among GCS for overload mitigation. The mobile MVESs couple the operations of power and transportation systems. To quantify the impact of MVESs on the on-road traffic, power and transportation systems have been jointly modelled and managed. Then, modelling and optimization methods for MVES management have been introduced. A case study has been conducted to validate the effectiveness of the proposed MVES management framework. To facilitate MVES development in the future, there are still challenges such as the incentive mechanism design, battery management, and security and privacy issues of communication.

This article should be useful for further research on PEVs as energy storage devices in the coupled power and transportation systems.

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