Towards Efficient Battery Swapping Service Operation Under Battery Heterogeneity

Xu Zhang, Yue Cao, Linyu Peng, Naveed Ahmad, and Lexi Xu

***Abstract*—The proliferation of electric vehicles (EVs) has posed significant challenges to the existing power grid infrastructure. It thus becomes of vital importance to efficiently manage the Electro-Mobility for large demand from EVs. Due to limited cruising range of EVs, vehicles have to make frequent stops for recharging, while long charging period is one major concern under plug-in charging. We herein leverage battery swapping (BS) technology to provide an alternative charging service, which substantially reduces the charging duration (from hours down to minutes). Concerning in practice that various battery is generally not compatible with each other, we thus introduce battery heterogeneity into the swapping service, concerning the case that different types of EVs co-exist. A battery heterogeneity-based swapping service framework is then proposed. Further with reservations for swapping service enabled, the demand load can be anticipated at BS stations as a guidance to alleviate service congestion. Therefore, potential hotspots can be avoided. Results show the performance gains under the proposed scheme by comparing to other benchmarks, in terms of service waiting time, etc. In particular, the diversity of battery stock across the network can be effectively managed.**

***Index Terms*—Electric Vehicle, Battery switch, Transportation planning, E-mobility.**

I. Introduction

FOLLOWING advances in sustainable energy development, Electric Vehicles (EVs) of electricity propulsion-based are starting to penetrate the transportation landscape. Fueled by the rapid development in green and intelligent transportation systems, various incentives from government or industries worldwide are promoting EVs to act as key enabler for the evolution of sustainable transport technology. Inevitably, EVs are gaining the popularity of general public, by an expansion of over 50% from 2016 according to [1].

As compared to traditional gasoline-powered vehicles, the main problem with EV transportation is long driving range. Limited cruising range requires EVs to charge frequently during a long journey, leading to the degradation of the travel efficiency as well as driving comfort. Besides, locating convenient charging services are also among the major obstacles [2].

It thus becomes imperative to tackle the challenges relating to Electro-Mobility (E-Mobility) for efficiency concerns. There have been many solutions toward the issue of charging management [3]–[5], [7]–[10]. One major focus is on "when/whether to charge" [3], when scenarios are simple and EVs are usually parked (e.g., at home or charging stations (CSs), etc.). In such cases, vehicles are seen as stationary loads with no spatiotemporal properties.

Considering the mobility nature of EVs, however, recent research efforts start to show great interests in a more practical scenario where EVs on-the-move. Consequently, "where to charge" (or E-Mobility) becomes a critical issue [4], [5]–[8]. In such cases, EVs are strategically assisted to drive toward an appropriate CS during their journey, e.g., by accounting for the waiting time for charging service [9], [10]. To avoid CS hotspots where EVs may be concentrated, charging reservations from EVs are suggested to be made in advance at the selected CS [11], [13], [14]. As such, congestions can be predicted at a specific time of a particular CS. Benefited from such intelligence on CS-selection, charging Quality of Experience (QoE) can be considerably improved.

While these plug-in charging solutions have shown their effectiveness, a near 100 percent charge still requires over 30 minutes based on fast charging power [15]. It is clear that it will be very challenging to overcome the disadvantages like longer time and battery degradation via existing fast charging technology. As such, it certainly appears that an alternative method of charging is needed. So, battery swapping (BS) could be a viable option that provides a promising option in a cost-effective way [17]. It takes only several minutes to replace a depleted battery with a fully-charged spare, comparable to a gas-powered vehicle. There have been a few works on the aspects of energy scheduling or battery swapping station (BSS) deployment [18]–[26]. As of yet, these research works are mainly based on a single type of battery running for all EVs, which is lack of practical application.

Nonetheless, considering many manufacturers in market, batteries are generally not compatible with each other. For instance, Nissan Leaf uses the proven lithium-manganese (LMO) battery,

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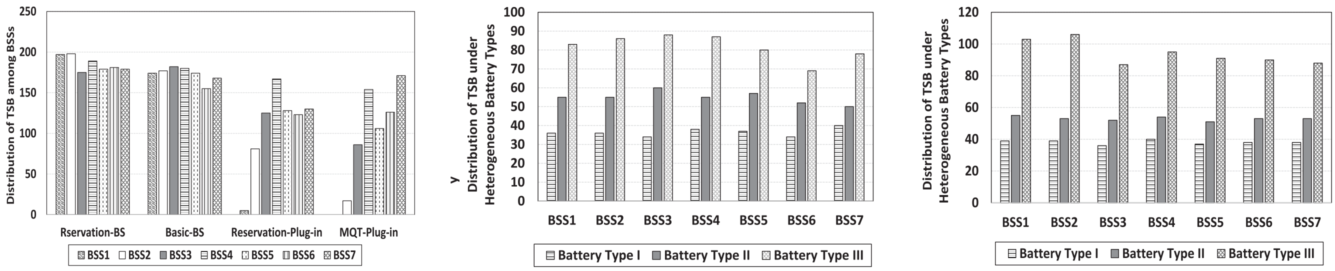
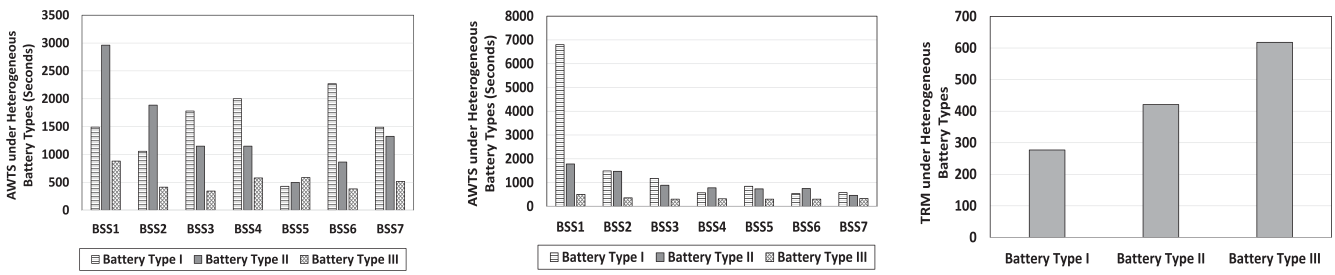


(a) (b) (c)

Fig. 7. Distribution of TSB among BSSs: (a) under different schemes, (b) heterogeneous battery distribution under Basic-BS mode, and (c) heterogeneous battery distribution under Reservation-BS mode.



(a) (b) (c)

Fig. 8. Performances under Battery Type Level: (a) AWTS under Basic-BS mode, (b) AWTS under Reservation-BS mode, and (c) TRM under Reservation-BS mode

in terms of waiting times. And results from Fig. 5-D(a) provides a more direct explanation of such relationship, along with previous evaluations of Fig. 5(a) and Fig. 6(a).

As for the TSB distribution related to battery heterogeneity, Fig. 5-D(b) further shows the distribution of TSB for each battery type at every BSS under a basic-BS scheme. As observed, the TSB values for each type of battery achieves a relatively balanced distribution among the network. This implies that the diversity of battery stock across the network can be effectively managed. As noticed, at each BSS, the TSB values are different for each battery type, with battery type III accounts for the most demand. Such differences are closely associated with various SOC values. EVs assigned with high SOC values generally suffer from short driving ranges and thus, they require more frequent BS services.

Further considering BS reservations, Fig. 5-D(c) shows the distribution of TSB for each battery type over the network. Similarly to Fig. 5-D(b), a desirable balancing is achieved, while more readily switchable batteries can be maintained at each station. This is mainly benefitted from the joint concern on AWTS and TSB for BSS selection.

E. *Performances Under Battery Type Level*

As for performances considering battery heterogeneity, Fig. 5-E further shows AWTS and TRM on the basis of battery type-level. Not surprisingly, with reservation-enabled, each type of EVs suffers from less waiting times at BSSs as compared to the Basic-BS mode in Fig. 5-E(a). As noticed, EVs of type I still have to wait relatively long period especially at BSS 1 as shown in Fig. 5-E(b), which implies that BSS 1 is highly concentrated with type-I vehicles. However, for the rest of BSSs, each type of EVs enjoys relatively balanced AWTS under the Reservation-BS mode. As observed from Fig. 5-E(a) and (b), EVs of type I suffer from longer waiting times, while type III EVs enjoy the least. This implies that more EVs of type III can receive BS services, which is in accordance with the results in Fig. 5-D(b) and (c), where more EVs of type III can be replaced with full-charged batteries. Such relationship further proves the effectiveness of the proposed scheme.

Fig. 5-E(c) shows the TRM for each battery type under the Reservation-BS mode. Intuitively, EVs of type-III make more frequent reservations for BS services as compared to other types, while type-III EVs report the least BS reservations. Based on previous evaluations, EVs of type-III receives the most BS services while enjoying the least AWTS, and thus more vehicles of this type will become in motion again. In other words, they are more likely to run out of energy once more. Therefore, a new round of BS services is in demand, which would incur more frequent reports for BS service reservations.

VI. Conclusion

In this paper, we introduce battery heterogeneity into the swapping service, in terms of various EV battery types. In order to facilitate the intelligent BS station-selection concerning such practical concern, a battery heterogeneity-based swapping service framework is then proposed. The proposed scheme is further enhanced with reservations for efficient swapping services, such that the demand load for a particular battery type can be anticipated at a particular BS station. A series of simulation studies are executed to evaluate the viability of the proposed framework. By comparing to other benchmarks, results show the viability of the proposed scheme for determining an optimal BSS-selection. In particular, the swapping load can be well balanced over the network based on the proposed framework. Meanwhile, the diversity of battery stock across the network is able to be effectively maintained for achieving an optimal E-Mobility system.

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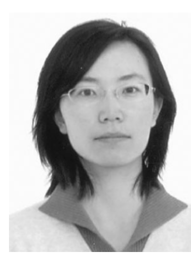

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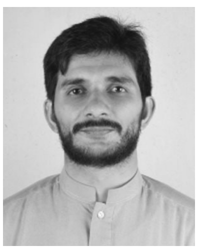

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