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Shared Autonomous Electric Vehicles and the Power Grid: Applications and Research Challenges

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***Abstract*—The future of transportation will be shared, autonomous, and electric, leading to a paradigm shift in the transportation domain. This shift comes with opportunities and challenges for the electric power system. For example, the charging of large shared autonomous electric vehicle fleets can be controlled in a centralized way and these vehicles can also provide ancillary services such as demand response or frequency regulation for the electric power system. In this paper, we give an overview of the research residing on this boundary between transportation systems and electric power systems. We discuss shortcomings and identify potential topics of research that we believe need to be addressed to foster the successful integration of shared electric vehicle fleets into the power system.**

***Index Terms*—shared autonomous electric vehicles, smart grids, ancillary services, smart charging, vehicle grid integration**

I. Introduction

Among experts, it has become consensus that the future of transportation will be shared, autonomous and electric [1]. Worldwide, car sharing services and so-called transport network companies (TNCs) such as Uber or Lyft are becoming more and more popular. Because of an increasing environmental awareness, interest in electric mobility especially with regards to car sharing services is growing. While electric vehicles (EVs) are still associated with some challenges such as reduced range and longer charging times in comparison to conventional cars, there already exist car sharing programs like Moov'in[1] in Paris, BlueSG[2] in Singapore or Carma[3] in San Francisco that operate fleets purely consisting of EVs. TNCs such as Uber also encourage the usage of EVs on their platforms to reduce greenhouse gas emissions[4].

In addition to sharing and electrification, the introduction of autonomous driving (AV) will trigger another important change in the transportation sector in the coming decade, as automakers and companies are actively planning to commercialize AV technology [2]. Combining these three aspects (sharing, electrification and autonomy), the evaluation of so-called shared autonomous electric vehicles (SAEVs) is an emerging and interesting research topic. SAEVs differ from normal EVs in terms of duty cycles, human-less operation and thus decoupling from regular working hours, and capabilities such as self-organized charging.

[1]www.moovin.paris/ [2]www.bluesg.com.sg/ [3]www.gocarma.com/
[4]www.uber.com/gb/en/u/drive-journey-to-electric/

Recent literature has looked into the benefits [3], cost analyses [4], acceptance [5], and environmental impact [6] of SAEVs. In addition, there exist a number of studies that address the interactions of these fleets with electric power systems in a more abstract way [7], [8]. For instance, the placement of charging stations not only affects the service efficiency and customer experience [9] but also the voltage stability and reliability in low voltage distribution grids. From a charging management perspective, charging processes of large SAEV fleets could be better controlled than in privately owned EVs and the vehicle batteries could be used to provide various ancillary services such as frequency control or peak shaving [7]. In summary, the large-scale deployment of SAEV comes with a number of opportunities and challenges for both the transportation and electric power system, some of which are well understood, whereas we believe that others need to be studied in more detail.

In this paper we want to contribute to the successful integration of SAEV fleets by 1) providing an overview of existing research situated on the boundary between transportation and power systems (Section II) and 2) by identifying current shortcomings and research gaps to derive recommendations for future research directions (Section III).

II. SAEVs and Power Grid Integration

In our literature review we identified three major fields, situated on the boundary between transportation and power systems (see Figure 1). These research fields which we will discuss in this section include smart charging strategies for SAEVs which, for example, can take the integration of electricity generated by renewables or load shifting into account. The second field is the topic of charging station placement under mobility and electric grid constraints. The third research field is the general potential of power grid integration.

A. Smart Charging Management of SAEVs

The potential of smart charging management for privately owned EVs in smart grids is well documented in many publications. A good overview is provided in the survey works Wang et al. [10] and Hu et al. [11]. However, many of the proposed charging strategies are often not transferable one-to-one to SAEV fleets, as privately owned EVs can be charged during their downtime at home or during office hours. In order to avoid additional peak loads and possible grid congestion of

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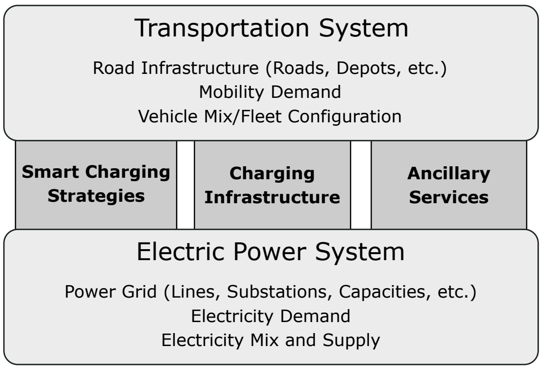

Fig. 1. Major interaction points between transportation and power systems

low voltage distribution grids in the evening hours, charging processes are often shifted to hours with low demand in the night and morning hours [10]. Potential charging times for SAEVs, however, highly depend on their duty cycles stemming from mobility demand or freight volume.

Still, charging cycles of SAEVs are often foreseeable and controllable, as they can be routed to a charging station when they are currently not in use. This requires optimized routing and relocation for transportation services in order to avoid long waiting times for passengers. A novel methodology for the optimized charging of SAEVs together with optimized routing and relocation is proposed by Iacobucci et al. [12]. The presented model uses two different time scales at which charging and transportation service have to be optimized.T The long-term scale optimization minimizes the charging costs of the vehicles taking into account dynamic electricity prices. In order to minimize waiting times for passengers the vehicle routing and re-balancing is optimized at shorter time scales such that the charging constraints from the long-term scale are fulfilled. Results show that the charging costs can be reduced by $10\,\%$ to $43\,\%$ depending on the used price profiles.

A general challenge for SAEV fleets is the generation of an online charging schedule. The schedule can be optimized with regards to various metrics, such as passenger waiting times, electricity pricing, or queuing times. The work by Tucker et al. [13] addresses this problem by optimizing charging decisions and re-balancing processes. In the between-ride state, which is described as the state after completing a trip, the vehicle must be scheduled for charging and then routed to the next pick-up location. The authors develop an online heuristic which makes decisions considering multiple pick-up/drop-off locations, multiple charging facilities, operational costs, grid integration of renewables, and re-balancing.

Another approach for the smart charging management of SAEVs is presented by Zhang and Chen [14]. To quantify the impacts of vehicle and charging infrastructure choices on fleet energy-related costs, they introduce a discrete-time, agent-based model of SAEV fleets to apply different smart charging management strategies based on dynamic electricity tariffs or renewable energy sources. They assume that fleet operators can coordinate charging events centrally as long as the vehicle is not being used. They conclude that electricity costs can be reduced and, when using photovoltaic smart charging, a self consumption rate of $99\,\%$ can be reached.

One of the first steps towards the coupled analysis of SAEVs and power distribution grids in the context of smart charging management is given by Estandia et al. [8]. The authors describe an optimization-based modeling approach to jointly control an SAEV fleet and several power distribution networks. They carry out and optimize the power flow problem in distribution networks with radial network structures and subsequently, study the coordination under balancing constraints. The main findings of a case study in Orange County show that coordination can help reduce $99\,\%$ of the overloads and $50\,\%$ of the voltage drops in comparison to a baseline case without charging management.

B. Charging Infrastructure Planning

Most of the literature on the placement of charging stations for privately owned EVs [15] is not directly applicable to SAEV fleets. Fleets differ significantly from private vehicles in terms of mobility patterns, duty cycles and also available charging stations, requiring specialized placement strategies such as the ones presented in [16], [17], and [18].

Zhang et al. [16] address the joint fleet sizing and charging system planning problem for a fleet operator of autonomous EVs for passenger and goods transportation in an intercity scenario. The authors identified two major problems: 1) the size of a fleet to fully exploit the potential of the fleet and reduce its costs and 2) the planning for the charging system. Both problems are strongly connected to each other. The authors propose a mixed integer linear program and present how a higher charging power reduces the required number of chargers and also allows for smaller fleet sizes.

Implications of charging infrastructure decisions for the operation of SAEV fleets are given by Chen et al. [17]. Based on a discrete-time agent-based model, different scenarios with respect to different charging infrastructure and EV types are considered. The authors also examine the impacts of vehicle range and charging time on the charging station sites and fleet size as well as the trade-offs between investments in vehicles and charging infrastructure and user benefits. An SAEV is modeled using different states - if the vehicle is in the charging state and there is no charging station within the remaining range of the vehicle, a new charging station is generated. This approach therefore does not introduce a limit on the number of charging stations. The authors show that fast DC charging can drastically reduce concurrent charging during the peak period in comparison to AC charging whereas the costs per mile increase by around $15\,\%$.

To consider upper bounds on the number of charging stations, Loeb et al. [18] build a simulation framework for charging station placement which is based on Chen et al. [17]. The authors simulate robust locations for charging station placement as well as the impact of battery ranges, charging times, and fleet sizes on SAEVs system performance. The charging station generation is similar to the method proposed by Chen et al. [17] with the difference that stations with fewer than 1.2 visits per day are removed after a 30-day simulation. In the considered scenarios, fast charging and greater vehicle ranges reduce the number of required charging stations.

More recently, Vosooghi et al. [9] discuss the effects of charging station placement on the performance of SAEV fleets. To this end, they perform an agent-based simulation of SAEVs across a metropolitan area in France. In order to find charging station locations two optimization models are used. The first one is based on the maximal covering location problem and the second model is based on a warehouse allocation problem. The best performance level is reached when the number of outlets of normal chargers (22 kW) is increased to 33 %-67 %.

C. Ancillary Services and the Potential for Grid Integration

In Iacobucci et al. [7] the authors discuss the potential integration of passenger transportation SAEV fleets into the electric power system. The authors develop a simulation model for the evaluation of the SAEV fleet when a heuristic charging strategy is deployed. Apart from the impacts on the transportation system, the authors also test the potential of the SAEVs for providing operating reserve. Results show that a fleet of SAEVs can provide operating reserve even at peak transportation demand without a significant impact on the quality of the transportation service.

Iacobucci et al. also studied the synergies of SAEVs and renewables in microgrids [19]. The authors develop a simulation methodology for optimizing vehicle charging in a virtual power plant or microgrid. Different configurations of the virtual power plant and microgrid are considered, e.g. with or without grid connection, solar energy or wind energy. Based on these configurations the potential of aggregated storage provision in combination with renewable energy sources is investigated. The study shows that SAEV fleets are effective at reducing the overall costs in the virtual power plant.

Similarly, Sha et al. study the integration of SAEVs and microgrids in a smart city context [20]. The authors develop a framework for cross-disciplinary analysis to understand city-wide mobility-energy synergy to improve the self-sufficiency and resilience of solar-powered microgrids by operating SAEV fleets. A (N-1) resilience-constrained fleet dispatch problem is proposed. In a New York City test scenario, the self-sufficiency of microgrids via the spatial transfer of electricity can be improved by around 53 %. Additionally, the microgrid resilience which depends on demand volumes and patterns, photovoltaic installation, and the fleet's state of charge when disruptions occur can be increased.

A three-layer architecture for SAEV fleets and energy service management in future smart cities is proposed by Tan and Leon-Garcia [21]. The first layer is comprised of the transportation network, the second layer includes the EV network and the third layer the power network. The authors give an overview of the disruptive transformation for each layer and define the concept of autonomous flexibility-on-demand. The vision of autonomous flexibility-on-demand is that SAEVs provide charging flexibility as a service on demand for the electric power system. In order to create synergies between SAEVs and autonomous flexibility-on-demand, key challenges such as planning of the infrastructure of the electric power system as well as charging control of SAEVs are identified.

III. Research Directions

In this section, we discuss the limitations we have identified in the reviewed literature as well as present promising research directions that we believe need to be addressed for the successful introduction of SAEV fleets, especially with regards to the underlying power system.

A. Modeling and Simulation

Naturally, most of the literature evaluates solutions for the deployment of SAEV fleets by means of simplified analytical models or simulation. We believe that more work is mandated to ensure the usefulness of the results obtained with these methods. In terms of mobility, basic traffic simulations that merely represent traffic flows and volumes are insufficient. These simulators often include methods such as turn-based probabilities to calibrate the traffic flows. While this approach generates more realistic traffic volumes, it will not yield realistic trips for individual vehicles. Moreover, EVs, especially when considering SAEV fleets, will take multiple trips over a day. These trips deplete the battery depending on the vehicle parameters as well as the state of traffic, and the vehicles might even be charged in between trips. It is therefore necessary to track the simulation state of a vehicle over a multitude of consecutive trips. In order to evaluate vehicle fleets, authors should focus on simulating individual mobility over longer periods instead of only traffic.

From this it follows that validated mobility models are required to improve the fidelity of simulation studies. For example, if the SAEV fleet under examination is a car-sharing fleet, then, a validated demand model of this transportation mode is required. If it is a commercial fleet, then the duty cycles of these fleets need to be realistic in order to obtain useful insights. Additionally, background traffic and environmental impacts will significantly impact the battery state of charge of an EV. The same trip will drain considerably more energy when the vehicle is stuck in traffic or when auxiliary consumers such as air conditioning are turned on. Also, smart charging management can lead to additional mileage or even cause traffic congestion. These aspects are usually neglected in simulation studies.

An important step and interesting research direction is the coupling between microscopic mobility and electric grid simulations [22]. This allows to address the problem that current research (e.g., [12], [14]) usually does not consider local transmission capacities or spatial grid imbalances. For some studies, offline coupling, e.g., in the form of charging load traces, can be sufficient. These trace files can be an input to the power grid simulation to understand whether the power grid has the necessary capacity to support the charging of the fleet. Such a setup might also be feasible to evaluate voltage drops, grid congestion, or harmonics in the power system [23]. When it comes to smart charging mechanisms that take into consideration the currently available capacity or electricity pricing, a bidirectionally coupled approach can be useful. The mobility simulation notifies the power system simulation of a charging event (e.g., paired with an electricity demand or a price threshold) and the power system simulation will return the currently available charging power. In other domains such as Vehicle-to-X communication, there already exist common frameworks that combine different simulators via specialised interfaces [24]. While efforts have been made to couple power and mobility simulation using High Level Architecture (HLA) or Functional Mock-Ups (FMU) [25], to the best of our knowledge, there exists no freely available coupled simulation framework or a tailored protocol to connect microscopic mobility and power system simulators.

Obtaining generally valid results is often not possible as different cities exhibit specific mobility and environmental patterns. Many challenges such as the charging station placement problem or the impact on the power grid require researchers to spend a considerable effort to create a validated underlying scenario. Therefore, to compare several fleet and charging management strategies, we believe that a common scenario would be beneficial. Unfortunately, data regarding the power system is often deemed highly sensitive due to security concerns. Mobility data is likely easier to come by even though precise origin-destination pairs, especially when analyzing commercial vehicles fleets will be challenging to obtain. The research community could thus benefit from a set of synthetic scenarios consisting of a road network, SAEV and other mobility demand, a power system with a resolution down to the substation and line level as well as information on dynamic background load. Such scenarios could serve as baselines for the comparison of various approaches as well as a first indication of the feasibility of a given approach for real-world deployment.

B. Fleet and Grid Synergies

Smart charging of SAEV fleets directly affects the power grid and interesting synergies which take both mobility and power grid constraints into account have already been discussed in the literature [12]–[14]. It has been shown that electricity costs can be reduced from a fleet operator perspective and electricity generated by renewable energy sources can be better integrated. Nevertheless, it is also an important research direction to address the impact on low voltage distribution grids on a microscopic level to investigate grid parameters such as voltage drops or phase imbalances.

From our point of view, decentralized charging hubs for SAEVs offer great opportunities to combine the battery capacity of various SAEVs for ancillary service provision. The provision of ancillary services can be an additional source of income for SAEV fleet operators and can help distribution system operators to stabilize their power grid. Novel coupling approaches between transportation systems and electric power systems are needed in order to determine the exact relationships between the satisfaction of mobility requests on the one hand and the requirements for grid services on the other. In order to evaluate the interactions, researchers should focus on identifying key parameters to better understand the limitations and possibilities one system offers the other in terms of ancillary services provision. Frequency regulation or operating reserve provision are of particular interest, as they are not sufficiently considered in the literature.

SAEV fleets with busy duty cycles (e.g. buses or lorries) will suffer from the effects of battery aging [26]. The operators of larger fleets will have to regularly deal with the replacement and the recycling of old batteries. These batteries could potentially be used inside the depot as storage devices to further contribute to the reduction of energy costs and to support the stabilization of the connected power system. We would like to see more research into the sustainable (and feasible) use of old batteries with respect to SAEV fleets.

The work of Iacobucci et al. [7] and Sha et al. [20] already show the potential of SAEVs in the context of microgrids and renewable grid integration. At this point we want to introduce the idea of depot charging in combination with second life batteries and roof-topped photovoltaic installations. This combination offers great potential for fleet operators to become more independent of the energy supplier, as the self sufficiency rate can be increased and also ancillary services can be provided. Therefore, we recommend to investigate this setup especially for SAEVs, taking into account constraints resulting from both the mobility behavior and the power grid.

In terms of charging infrastructure placement, the discussed literature mainly address measurements regarding fleet sizes and the performance of SAEV fleets in terms of transportation systems. A more detailed analysis of the effects on the low or medium voltage distribution grids is missing, although existing works of charging infrastructure placement for EVs in general such as Huang et al. [27] or Liu [28] take the power grid into account. There seems to be a lack of work on the charging station placement for SAEV fleets which particularly considers the power grid and associated constraints.

C. Vehicle to Grid communication

The recent finalization of the ISO/IEC 15118 Vehicle-to-Grid (V2G) communication protocol to enable the communication between EVs and the charging station opens up a wide range of new 'smarter' charging strategies, replacing the widely used pulse width modulation communication which only allows basic signaling to control the charging power.

The duty cycles of SAEVs will impact the effect of "gridable" vehicles, that can act as storage and return energy to the grid. While these V2G applications have received a great deal of attention from the research community [29], the effect of a paradigm shift caused by SAEVs has not. Often, the benefits of V2G applications are based on the assumption that vehicles are parked 90% of the day and that charging (and discharging) can be scheduled rather freely. These assumptions might no longer hold under the mobility as a service paradigm, where individual car ownership decreases and fleets from different SAEV providers dominate the streets. It would be interesting to see the potentials and limitations of V2G applications under these constraints, especially given ideas to re-purpose autonomous vehicles during off-peak hours, to operate mix-purpose fleets, e.g. to transport freight and passengers [30].

A better coordination between fleet operation and the smart grid could further support reaching environmental goals as charging during preferable conditions for the feed-in of renewable energy could be targeted. SAEV fleets can then not only contribute to reducing the urban heat island effect but also support the phase-out of fossil fuel power plants.

IV. Conclusion

In this paper we discussed research connecting transportation and electric power system with regard to the introduction of SAEV fleets. We identified three major interaction points: smart charging strategies, charging infrastructure as well as ancillary services. We observe that often when discussing SAEV fleets, a detailed discussion on the impact on low voltage grids is missing. We believe that a more connected research approach is mandated to support the successful integration of SAEVs. One possible way to achieve this is the coupling of microscopic mobility and power systems simulators. Furthermore, SAEV charging optimization models should also include constraints from the power system, such as existing capacities, operating reserves, or renewable energies. We believe that only a holistic approach can ensure that the envisioned paradigm shift in the transportation domain creates synergies with future smart electric power systems.

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